Range Commanders Council

PROCEEDINGS OF

THE 1990 THUNDER AND LIGHTNING SEMINAR AND THE 3D LIGHTNING WARNING WORKSHOP

FEBRUARY 1993

PHYSICAL SCIENCES LABORATORY
NEW MEXICO STATE UNIVERSITY
LAS CRUCES, NEW MEXICO

METEOROLOGY GROUP

WHITE SANDS MISSILE RANGE
KWAJALEIN MISSILE RANGE
YUMA PROVING GROUND
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DETACHMENT 2, SPACE AND MISSILE SYSTEMS CENTER

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METEOROLOGY GROUP
RANGE COMMANDERS COUNCIL

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PREFACE

The Range Commanders Council (RCC), Meteorology Group (MG), sponsored a Thunderstorm and Lightning Seminar at the 68th MG Meeting held 27 February 1990 at the Physical Sciences Laboratory, New Mexico State University, Las Cruces, New Mexico. The primary objective of this seminar was to provide information and exchange theories on sensors, techniques, and applications relating to lightning and thunderstorms. One of the presentations, for example, describes a Thunderstorm and Lightning Tutorial available from NASA. Also included in the proceedings is a 5th Weather Wing Forecaster Memorandum titled "Lightning Detection System Acquisition and Applications." This memorandum provides information on the operational aspects of lightning detection sensors and how they may be used as well as advantages and limitations of the various systems and sensors discussed. The papers contained herein should provide information and resources on the various aspects of lightning and thunderstorm phenomena.

As a result of the seminar, the Meteorology Group formed the Lightning Prediction and Detection Committee. One of the committee's objectives is to periodically conduct lightning workshops. In August 1992, the 3d Lightning Warning Workshop was held in Salt Lake City, Utah. The first task for this committee was the initiation of a survey of lightning instruments and procedures used at the various ranges and organizations. The results of this survey are included in this document.

TABLE OF CONTENTS

INTRODUCTION

The Lightning Prediction and Detection Committee (LPDC) formally came into being at the 68th Meeting of the Range Commanders Council/Meteorology Group (RCC/MG), August, 1990. However, the *Thunder and Lightning Seminar* (February, 1990, Las Cruces, NM), which was held in conjunction with the 67th RCC/MG meeting and hosted by White Sands Missile Range, can be considered the first official activity of the LPDC. Next, in early 1991, the LPDC conducted a survey to determine the importance of lightning at the various RCC-member and associate-member ranges.

Several years ago, one DOD organization was alleged to have asserted that, "We know everything there is to know about lightning." Notwithstanding that unfounded pronouncement, ongoing research continues to provide new information about this important global phenomena. Unfortunately, those individuals responsible for making lightning predictions and issuing warnings often have neither access to practical information nor the tools for effectively performing that important aspect of their jobs.

This RCC document consists of seminar and workshop proceedings and the results of two surveys. The intent is to provide user-oriented lightning prediction and detection information to those who need it.

HISTORY

In 1987, the membership of the Range Safety and Meteorology Groups of the RCC participated in an independent lightning survey conducted by the individual who subsequently became the LPDC chairman. The responses revealed that the ranges had a definite need to obtain and desire to share lightning-warning information. With this in mind, the *Lightning Threat Warning Workshop* (September, 1987, Cocoa Beach, FL) was organized and sponsored by the Lawrence Livermore National Laboratory. The workshop was well-attended, successful, and resulted in the formation of the *Interagency Lightning Threat Warning Working Group*. After searching for a parent organization, this working group was invited to affiliate, appropriately, with the RCC/Meteorology Group. Although the LPDC membership is different from that of the original working group, the intent of the working group is fulfilled by the LPDC charter.

CHARTER AND OBJECTIVES OF THE LPDC

Charter

Identify mutual problems, share knowledge and techniques, and serve as the focal point for issues associated with the prediction and detection of lightning.

Objectives

Suggest and/or recommend equipment and procedures that can:

1. Enhance safety.
2. Reduce down time for "at-risk" activities.
3. Provide timely and credible information to duty weather forecasters.

To fulfill its charter and achieve its objectives, the LPDC will seek to:

1. Identify and coordinate common range problems and solutions.
2. Periodically conduct lightning prediction and detection workshops.
3. Track new technology, develop methods to facilitate technology transfer, and communicate needs to the scientific community or industry, as appropriate.
4. Identify and recommend criteria for selection, siting, and management of instrumentation.

It is important to recognize that although common range problems have been identified by means of surveys and several workshops have been held, little has been done to satisfy items 3 and 4 above.

PROCEEDINGS OF THE 1990

THUNDER AND LIGHTNING SEMINAR

MISSING PAGE

2

THUNDERSTORM AND LIGHTNING SEMINAR

PHYSICAL SCIENCE LABORATORY
NEW MEXICO STATE UNIVERSITY
LAS CRUCES, NEW MEXICO

27 FEBRUARY 1990

MR. RICHARD HASBROUCK, CHAIRMAN
Lawrence Livermore National Laboratory

0830	THUNDERSTORM ELECTRO-DYNAMICS AFWL, Kirtland AFB, NM	MAJ Robert Gardner
0900	PHENOMENOLOGY OF EARTH'S ELECTRIC FIELD AND DETECTION OF LIGHTNING AND ELECTRIC FIELDS Airborne Research Associates, Weston, MA	Mr. Ralph Markson
0930	THUNDERSTORMS AND THUNDERSTORM PROPERTIES FOR EARLY WARNING Langmuir Laboratories, New Mexico Institute of Mining and Technology, Soccorro, NM	Mr. William Rison
1000	THUNDERSTORM DETECTION PROGRAM AT EASTERN TEST RANGE Eastern Test Range, FL	CPT William Bauman Mr. Michael Maier
1030	BREAK	
1100	LIGHTNING AND THUNDERSTORM PROGRAM AT NASA, WALLOPS FLIGHT CENTER NASA Wallops Island, VA	Mr. John Gerlach
1130	LUNCH	
1300	LIGHTNING RELATED CURRENTS IN CONDUCTORS Electrical Engineering Dept, Penn State University, State College, PA	Mr. Leslie Hale

1330	INDUCED LIGHTNING STUDY OVER THE MIDWEST AFWL, Kirtland AFB, NM	CPT Andrew Terzakis
1400	LIGHTNING DETECTION AND SENSING AT THE NEVADA TEST SITE Weather Service, Nuclear Support Office, Las Vegas, NV	Mr. Carven Scott
1500	LIGHTNING THREAT WARNING AT THE NEVADA TEST SITE INTER-AGENCY LIGHTNING THREAT WARNING WORKING GROUP Lawrence Livermore National Laboratory, Livermore, CA	Mr. Richard Hasbrouck
1530	SAFIR Dimensions, Inc. Paris, Fr.	Mr. Philippe Richard
1600	THUNDERSTORM AND LIGHTNING VIDEO TUTORIALS U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM	Mr. Robert Olsen

COMPARISON BETWEEN FIELD MILL AND CORONA POINT INSTRUMENTATION AT *KENNEDY SPACE* CENTER: USE OF THESE DATA WITH A MODEL TO DETERMINE CLOUDBASE ELECTRIC FIELDS

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ABSTRACT

A new type of corona current instrument has been developed to measure electric fields at Kennedy Space Center (KSC). Previous limitations of this type of measurement, wind sensitivity and a voltage threshold "deadband", have been overcome. Mounting the corona needle at an elevated location reduces the influence of corona and electrode layer space charge on electric fields and makes possible measurement of space charge density. In conjunction with a space charge compensation model, this allows more realistic estimation of cloud base electric fields and the potential for lightning using data from ground based sensors than has been possible in the past. Electric field time series and contour maps derived from a mini-network of corona instruments at KSC when compared with simultaneous data from co-located field mills indicates much less space charge influence on measurements made at 20 meters height. Preliminary results of the model compared with data suggest the viability of this approach.

1. INTRODUCTION

1.1 The Problem.

The ability to map accurately the spatial and temporal variation of DC thunderstorm electric fields from the ground would provide an important improvement for prediction of the lightning hazard at Kennedy Space Center (KSC) both in regard to ground operations and the trigger lightning problem. Cloud-to-ground lightning originates in the lower portion of thunderclouds when local fields become sufficiently intense. Unfortunately, at KSC electric fields at ground level roll off (become space charge limited) at about 5 kV/m due to a blanket of space charge which forms near the Earth's surface under thunderclouds. In this state they provide little information on the magnitude or variation of the much more intense fields in the region between the top of the space charge layer and cloudbase. Differences between surface and cloud level electric fields maximize when the cloud fields are decreasing and changing polarity. At such times, the field component due to residual space charge can be approximately the same, but of opposite polarity, from the component due to cloud charges. This can result in apparently small fields at ground level when large fields still exist in the clouds. At these times the cloud and surface fields can even be of opposite polarity and we have observed this for a 5 min interval (1, Fig. 14). The inverse also occurs; sometimes there is little charge in the clouds but residual space charge near the ground can keep surface fields elevated, e.g., at the end of the storm for about 5 min or longer after the cloud field has dissipated.

Capability of mapping cloud electrification more accurately should provide substantial operational advantages at KSC where down time due to perceived "lightning threat" is considerable and lost time is very expensive. While some have suggested that more accurate ground level electric field measurements are unnecessary since operations will be called off anyway whenever the field mills record elevated values--this leads to stopping work sometimes when it is not necessary. In 1988 operations were halted near Shuttle Launch Pad 39B for 119 hours due to the existing conservative lightning alert criteria while lightning actually occurred for only 9 hours during those periods. More accurate information on cloud electric fields should help forecasters determine more precisely when to call an alert, the size of the area threatened, and when to call off the alert. It will be necessary to develop experience and confidence in the improved electric field data to allow less restrictive criteria, but better data seems a minimum requirement to improved lightning warning forecasting.

Presently there are plans to replace the existing field mills in the Kennedy Space Center/Cape Canavaral Air Force Station array with a newly developed inverted field mill. The existing mills are often unreliable, inaccurate and require considerable maintenance. The new mills should provide significant operational improvement. However, it is necessary to consider the general problem of measurement of thundercloud electrification with any instrumentation because space charge masks ground level sensors from cloud level fields.

1.2 Space Charge.

Space charge is produced over water by the electrode effect (2) in fair-weather and during thunderstorms, but since the ion production depends on field intensity, a much denser blanket of charge is created during thunderstorms (1). The breaking of bubbles from waves and surf also produces space charge (2). This charge can be blown over electric field sensors on adjacent land areas affecting the measurements. Over land, when thunderstorm fields exist, space charge is produced by point discharge (corona) from grounded objects. Because the vegetation, which covers much of the KSC region, is often 3-4 or more meters high, intense fields are not required. With a field of 1.5 kV/m, 4 meters above the surface the potential is 6 kV which is sufficient to cause corona from sharp points on vegetation. For example, near Field Mill 7 there are many trees and tall bushes and our measurements show point discharge occurs with fields as low as 1.5 kV/m.

Space charge from the electrode effect is of the same polarity as the charge in the base of the clouds and thus enhances field intensity near the ground; this effect can be as much as a factor of two (1). The corona space charge is of opposite polarity and reduces field intensity by as much as a factor of 5 to 10 compared to fields below cloud base (1,3,4). Such effects have made it difficult to use surface electric fields to determine with confidence cloud level electric field variations.

Space charge also influences instrument calibration. A grounded electric field sensor raised above the Earth's surface will not have a constant calibration factor in the presence of space charge because it has a "form factor" other than unity. The form factor is a number one multiplies the field mill output by to normalize it to conditions over flat ground (5). The form factor varies as a function of the local space charge which intercepts some of the field lines which would otherwise terminate on the plates of the field mill (5). For an inverted mill, where the lines reverse direction and approach the sensing plate from below, space charge above and below the mill will intercept field lines. Gathman and Trent (6) have considered the problem and find there is an inherent error of +/- 18% that can not be improved upon and that... "accurate measurements of electrostatic fields at the surface of the earth can be made only with a flush mounted meter." This is because a field mill flush with the ground would have a form factor of one and not be subject to space charge changing its form factor (5). But such an arrangement is impractical for an operational installation because of drainage, bugs, etc.

2. ADVANTAGES AND DISADVANTAGES OF CORONA INSTRUMENTATION

2.1 Advantages.

a. Instrument Maintenance. Corona systems are simple in principle and mechanically thus requiring little maintenance while having greater reliability than field mills. Four systems installed at the Department of Energy's Nevada Test Site operated normally from May until September 1988, when they were taken down, without any maintenance.

b. Environmental Factors. They are unaffected by rain, snow, sand or insects, all of which can influence field mill operation.

c. Cost. Their cost is comparable to that of field mills.

d. Sensitivity to Space Charge. Since the corona needle is often above a significant fraction of the space charge, and space charge only affects electric fields below it, corona instrumentation with an elevated needle is not as sensitive as an instrument on the ground to space charge from point discharge or the electrode effect.

e. Site Preparation and Maintenance. Because corona instruments are less sensitive to space charge, the areas around corona masts require less site preparation (clearing of bushes and paving) and less maintenance after installation (keeping bushes and grass cut).

f. Form Factor Consistency. With the sensor above some of the space charge, fewer lines of force from the cloud are intercepted by space charge ions than if the sensor is near the ground and its form factor is proportionately less affected.

g. No "Restricted Area" Requirement. Since the corona needle is mounted on top of a tall pole it is not easily accessible. Thus the area does not have to be restricted to keep people away from rotating machinery for reasons of safety. Also, people and movable objects must be kept away from any electric field sensor since their presence will change the field being measured.

h. Space Charge Compensation. The corona sensor can be mounted easily on a tall pole where its measurement, in conjunction with ground level electric field data and a model, can be used to provide a more accurate estimate of cloudbase electric field intensity than ground level observations alone. When used in an array, knowledge of space charge and the wind allows prediction of space charge affects on electric fields downwind.

i. Power Requirements. Corona instruments have no moving parts and require little power making them suitable for remote sites where solar cells and/or batteries are required. A corona system with the AC high voltage feature to eliminate the dead band presently requires 20 watts although this might be reduced in the future. In cases where very little power is available, it can be operated without the high voltage and then the power required is only a few watts, but the deadband would exist.

j. Portability. Because no site preparation or restricted areas are required and corona systems can be battery operated, sites can be changed or temporary corona arrays erected relatively easily. Williams et al. (7,8) have obtained useful measurements of electric fields and lightning transients using portable corona point sensors set up in arrays during microburst experiments at Huntsville and Denver.

2.2 Disadvantages/Special Considerations.

a. Accessibility. While the needles can be erected on short vertical supports within 1 or 2 meters of the ground, in which case the system would function much like other electric field instruments, this would sacrifice the benefits of a high mounting location. Erecting a tall mast and servicing the needle and corona pole at the top of the mast requires a bucket truck or climbing the pole. A preferable arrangement is to use a telescoping ham radio tower which can be lowered easily to the ground by one person. The corona masts can also be put on existing buildings and structures such as the 16 m wooden poles and wind towers used at KSC.

b. Point Errosion. With conventional corona current devices it is desirable to have a very sharp point to minimize the corona threshold voltage which increases as the tip dulls. The AC high voltage feature in the new instrument eliminates the sharpness requirement. Although there is some errosion of the point with time, the needle tip still retains a sharp edge and the power supply keeps it in corona. Calibration is not affected by changes in tip geometry with the AC high voltage feature.

c. Lightning. The elevated corona pole is in effect a lightning rod and it may be hit by lightning. While extensive statistics do not exist, it was found that for the 13 sensors installed at KSC for about half the 1988 thunderstorm season there were no direct lightning strikes. The tip of one needle was melted, evidently due to a close flash, but the pole and electronics were undamaged. Similarly, the four corona systems operated at the Nevada Test Site were not hit or damaged by lightning. Numerous storms occurred in both test areas. In atmospheric electrical folklore, going back to the days of Franklin, there has been speculation that a sharp lightning rod will not be struck, perhaps because of the corona produced cloud of ions reducing the electric field intensity in the volume just above the needle. It will be interesting to observe the statistics on strikes to corona poles in the future.

3. CORONA VS FIELD MILL DATA

There have been questions regarding interpretation of the corona records compared to the better understood electric field measurements. The corona instrument measures a current caused by the potential difference between the needle and surrounding atmosphere (the driving potential). Thus the instrument measures a current proportional to the atmospheric potential at the height of the needle, a potential created by the charges in the cloud overhead. (There is also an efficiency factor which is dependent on the needle-antenna mounting arrangement and ion cloud resistance; this factor is determined through calibration of the total system with a radioactive probe instrument.) By dividing the potential measured by the corona system by the height of the needle, the average field intensity in the layer from the ground to that height is determined. While in this report potential at 20 meters has been converted to an average electric field (potential divided by 20) for a more direct comparison with field mill data, there is no fundamental reason why electric field should be a preferential parameter for measurement of cloud electrification than potential. In electrical engineering "potential" is commonly used rather than "electric field". It is understandable that in the past electric field intensity has been the commonly used parameter to quantify thundercloud electrification since this is what is measured with field mills.

In sum, the corona instrument determines the potential at a known height while the field mill makes a direct measurement of field intensity close to the ground. If desired, a contour map of potential at 20 meters that would be comparable in all respects to the present surface electric field maps can be made and used in the same way as electric field contour maps to locate the position and movement of charged clouds. The same computer algorithms and plotting routines are used.

Why measure potential at the top of the pole rather than electric field? This is because it is difficult to make an electric field measurement on a tall supporting structure since it would normally be highly charged by induction. This charge will modify the local field being measured and raise the electronics to a potential of 100 kV or more. It is impractical to try to maintain electrical isolation in a field installation for extended periods of time and charge on signal wires running up the pole will also prevent this. Thus electric field measurements above the Earth's surface have generally been obtained from ungrounded platforms such as aircraft or balloons with signals telemetered to a ground station.

4. DISCUSSION

4.1 Corona Instrument Improvements.

In the past it was well known that corona currents could be used to monitor variations of electric fields qualitatively. Such instrumentation was subject to appreciable errors both due to sensivity to wind velocity (which make the system act like an anemometer) and to the fact that grounded points near the Earth's surface do not go into corona until thunderstorm fields of about 2 kV/m exist. Thus, even during thunderstorms conventional corona instruments do not function about 20-50% of the time (7). Both of these limitations have been overcome with the new corona instrument which is unaffected by the wind and has no corona threshold "dead band". The wind modulation was suppressed by including a 5 x 10^{10} ohm resistance in the input which effectively makes most of the IR drop between ground and the atmosphere occur across a known stable resistance rather than the variable resistance ion cloud around the corona needle (9). The deadband was eliminated by keeping the needle in corona with an AC high voltage powersupply. This provides a cloud of bipolar ions around the point at all times and a current will flow even during weak fair-weather fields. These improvements make it possible for relatively simple instrumentation to provide electric field measurements in fair-weather as well as during thunderstorms (10).

Figure 1 is a diagram of the corona mast part of a system which is mounted on top of a tall pole or tower. The other part of the system is a unit containing a current amplifier, power supplies, and a line driver (if the signal is sent over landlines) which is mounted near the base of the pole or tower.

4.2 Space Charge Effects.

As previously mentioned, corona currents and potentials measured above the ground are more representative of cloud electric fields than ground data (11). This can be seen in the electric field contour maps (to be discussed) where the lines pack in closely at the land-water interface because surface fields over land are suppressed by corona space charge while over water they are enhanced by the electrode effect space charge blanket.

Presently we do not know the statistics on what percent of the space charge lies below 20 meters under varying meteorological conditions, but the measurements by ourselves (1) and the French investigators (12,13) suggest that generally it is a significant fraction, sometimes on the order of 50%. There are several reasons for this. For corona space charge, the source lies close to the ground since grounded points go into point discharge. Corona space charge concentration is dissipated as it migrates upward due to electrical relaxation, eddy diffusion, and increasing electric field intensity with height. However, space charge from the electrode effect has the same polarity as the cloud charges which creates it. The electrode effect does not occur over land because it is destroyed by ionization from ground based radiation; it occurs over water, in a layer mostly below 50 m during thunderstorms (1) and fair-weather (14), because there is no ionization at the air-water interface (2). The electric forces from the cloud produced field oppose upward migration of electrode effect ions (they have the same polarity) which further leads to concentration of space charge close to the surface. Aerosols also are significant; Soula et al. (13) state "...the primary ions generated by the ground (corona) are likely to collide with aerosol particles and become slow ions. This process keeps a great part of the space charge close to the ground." All these factors lead to an accumulation of space charge near the ground which has a stronger influence on surface fields than fields above the ground.

5. FIELD MILL vs CORONA INSTRUMENT VARIATIONS DURING A THUNDERSTORM

Figure 2 is a map of the KSC field mill array (site numbers shown). The sites with co-located corona systems are circled and the area covered by the corona mini-network is within the dashed line rectangle.

Figures 3A and 3B are time series of electric field variations derived from field mills and and corona systems during the storm documented in the summer of 1988. Only measurements from sites where both the field mill and corona sensors were functioning properly were used and the data were processed identically. The solid line is for corona and the dashed line for field mill data. The ticks on the vertical axis are for (+) and (-) 6 kV/m. At Site 5 the traces are similar, presumably because the field intensity was too small to create much corona space charge. The sites generally are surrounded by bushes and trees within about 100 m, but Site 7 is on the edge of a swampy area with only low vegetation upwind which would not go into corona easily. Here the field mill trace amplitude is a little larger than the corona amplitude, possibly because of enhancement from electrode layer space charge. At Site 12, which is the only other land site in this study not surrounded by bushes, the traces are similar. At the rest of the land sites the corona derived field intensities are larger than those of the co-located field mills.

In Fig. 3B, at Site 21, where the field mill is in a low spot surrounded by high bushes, the maximum corona value is 3 times that of the field mill. However, the opposite occurs at the two causeway sites where the field mill intensities are greater than the corona values. This is caused by electrode layer space charge from over the water which is concentrated near the surface. At 1555 the field mill at Site 21 was indicating about 2 kV/m while the nearby Causeway West field mill was measuring 8 kV/m.

The next four figures depict electric field contours at ground level (from the field mills) and surface to 20 m average (computed from 20 m potentials) during the storm. At 1525 EDT (Fig. 4), the beginning of the storm before the space charge is generated, the corona and field mill maps are similar.

At 1535 (Fig. 5) the fields were increasing. The field mill (surface) data from the causeway were 2.5 times larger than the nearby overland field mill value at Site 21. However, for the corona data the reverse is true--the field was larger at 20 m over land than over the water.

At 1545 (Fig. 6) the surface value at Site 21 is half the surface value on the causeway while the 20 m values still are greater over land. The packing of contour lines for the field mill data at the land-water interface at the west end of the causeway is of particular significance. This is not seen in the corona data which shows a single charge center over Field Mill 21 and even spacing between contour lines.

At 1555 (Fig. 7) the ratio of water to land intensity for surface data is 4:1 while at 20 m the ratio is about unity. The relative smoothness, simpler pattern, and lack of large gradients in the corona contours suggests that the 20 m measurements are more representative of cloud electrification. Convective thundercloud cells typically are several km in diameter consistent with the corona derived contours.

6. NUMERICAL MODELING

While corona current measurements at 20 meters reduces space charge modulation of electric fields, when space charge is present above that height they do not completely portray electric field intensity at cloud base. Thus, we are developing a numerical model of electrical properties which, when fully implemented, will be used in conjunction with field measurements at two heights to estimate the electric field above the corona screening layer. Two versions are currently operating: a unipolar model following the approach of Chauzy and Raizonville (12) and a fully bipolar model after Chauzy and Rennela (15). The latter version has been modified to include more realistic turbulent transport (a variable eddy diffusion coefficient), creation of ions through non-discharge processes, and the electrode layer effect. The models are based on the budget equations for the volume concentration of small and large ions which include terms for ion production through ionization (bipolar model only) and corona discharge, as well as loss thru recombination (bipolar), attachment to aerosols (conversion of small ions to large ions), conduction and turbulent transport. It is planned to develop an extended version of the bipolar model which will include production of ions by radioactive decay and removal by horizontal advection. Both models have been tested and reproduce the theoretical results of earlier studies (12).

The current version of the bipolar model was used to simulate the electric field behavior observed from the field mills and corona systems at KSC. The time series of surface electric field (field mill) from Fig. 3B, Site 15, was used as input to the model. This site is not directly adjacent to any bodies of water but is fairly close to the causeway sites which were used for comparison. The model was run forward in time and the surface electric field values were forced to fit the data. The electric field profile was determined by integrating the space charge from the ground up with the surface field acting as the lower boundary condition. The model was run with a turbulent diffusivity of 1 m^2s^{-1}, a nominal aerosol concentration of 1 x 10^{10} m^{-3}, and a corona threshold of 1.5 kV/m.

Figure 8 shows the results of the simulation; the model field values are indicated at 20 m and 250 m. In the first phase the field is positive and barely exceeds the chosen threshold. So little space charge is generated that the effects on the field profiles are almost unobservable. A slight increase in the threshold and there would have been no space charge effects at all in this phase. This is consistent with the observations at virtually all of the stations shown in Figs. 3A and 3B. The fact that all stations indicate both surface fields and average fields (derived from the 20 m data) cross zero at the same time is further proof of negligible space charge; with corona space charge present surface electric fields cross zero before fields aloft (1,13).

In the second phase the surface field reverses and maximizes at -3 kV/m. The observations indicate that the field derived from the 20 meter potential measurements is about -4 kV/m, consistent with the simulation. The field at 250 m from the model tracks the surface field until the large negative swing. The upper values are on the order of -8 kV/m, similar to the causeway measurements. Since there is no corona space charge over the water (because there are no elevated grounded points) the fields there should not be influenced by corona space charge, except as it may be blown to the causeway sites from land areas. The overwater fields peak at about -10 kV/m, but there is expected to be some enhancement due to the electrode layer. In sum, between 15.7 and 16.0 hours the field aloft approached a value of about -10 kV/m while over land the surface value was only -3 kV/m and the average field derive from the 20 m data was -4 kV/m; this behavior was essentially simulated by the model using only the surface electric field time series.

7. CONCLUSION

By making potential measurements at the top of a high pole, in addition to electric field measurements at the ground, it is possible to estimate space charge density variation in the region between the elevated point and ground. These data can be used in conjunction with a model to determine the electric field above the space charge layer which will be approximately the same as just below cloud base. Thus, by having both corona instruments on poles and surface electric field data (from field mills or corona instruments) at the same location in a spaced array, it will be possible to obtain maps of the subcloud electric field over a region with allowance for space charge effects. This can be tested through comparison with simultaneous aircraft elecric field measurements. This approach offers the possibility of significantly improving the capability for determining lightning potential continuously over a region using only ground based instruments.

8. REFERENCES

1. Markson, R. and Anderson, B., "New electric field instrumentation and the effects of space charge at Kennedy Space Center", Proc. 1988 Conf. on Lightning and Static Elect., Oklahoma City, NOAA Special Rept., 94-102, ERL/NOAA, 1988.

2. Chalmers, J.A., Atmospheric Electricity, Vol. 2, 42 and 103, Pergamon, London, 1967.

3. Kasemir, H.W., Rust, W.D., and Holitza, F.J., "Final Report to KSC Contract CC-59753" (*Report on aircraft* electric field measurements over the KSC field mill network), NOAA/APCL (Boulder), 105 pp., June 1976.

4. Standler, R.B. and Winn, W.P., "Effects of coronae on electric fields beneath thunderstorms", Quart. J. Roy. Meteor. Soc., 105, 285, 1979.

5. Chalmers, J.A., op. sit., 136.

6. Gathman, S. and Trent, E.M., "Absolute electric field measurements using field mills, Atmos. Phys. Branch, Naval Res. Lab., Rept. 6538, 8 pp., 1967.

7. Williams, E.R. and Orville, R.E., "Intracloud lightning as a precursor to thunderstorm microbursts", Proc. 1988 Conf. on Lightning and Static Elect., Oklahoma City, NOAA Special Rept., 454-459, ERL/NOAA, 1988.

8. Williams, E.R., Weber, M.E. and Engholm, C.D., "Electrical characteristics of microburst-producing storms in Denver", Proc., 24th Radar Conf., Tallahassee, April 1989.

9. This technique was first suggested by L. Ruhnke and patented by NASA; L. H. Ruhnke, "A rocket borne instrument to measure electric fields inside electrified clouds", NOAA Tech. Rept. ERL 206-APCL 20 May 1971.

10. A patent is pending on the AC high voltage corona system.

11. Chalmers, J.A., op. sit., 247.

12. Chauzy, S. and Raizonville, P., "Space charge layers created by coronae at ground level below thunderclouds", J. Geophys. Res., 87, 3143, 1982.

13. Soula, S., Chauzy, S., and Faizoun, A., "The surface electric field as a warning criterion", in Proc. 1988 Int. Conf. on Lightning and Static Elect., Oklahoma City, NOAA Special Rept., 294-299, ERL/NOAA, 1988.

14. Markson, R., "Atmospheric electrical detection of organized convection", Science, 188, 1171, 1976.

15. Chauzy, S. and Rennela, C., "Response of the surface charge layer created by corona at ground level to external electric field variations beneath a thundercloud", J. Geophys. Res., 90, 6051, 1985.

9. ACKNOWLEDGMENTS

We wish to thank Derek Lane-Smith, Steve Marsh, Steve Trier, Drew Kendra, Keith Olsen and Rob Lankin for their help during this project. At KSC, Ron Wojtasinski, Program Manager, was most helpful in many ways and Bill Jafferis provided housing at the Atmospheric Sciences Field Station. This work was supported under NASA/SBIR Contract NAS 10-11412.

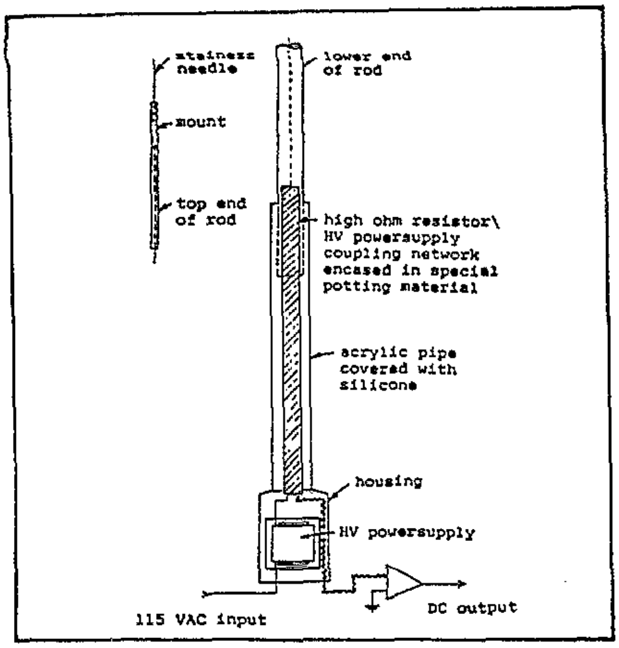

Fig. 1 Diagram of a 3-4 meter long corona mast assembly that goes on top of a pole, tower or building.

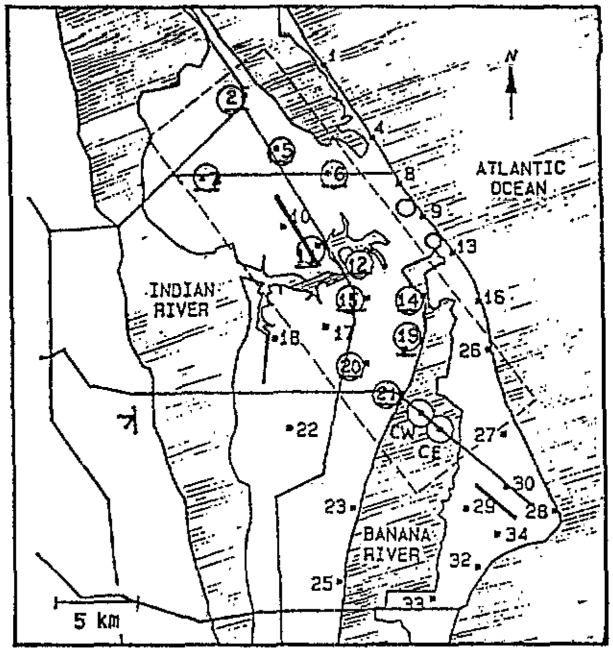

Fig. 2 Map of the KSC field mill network, area of corona sensors within dashed line. Causeway E and Causeway W are over water.

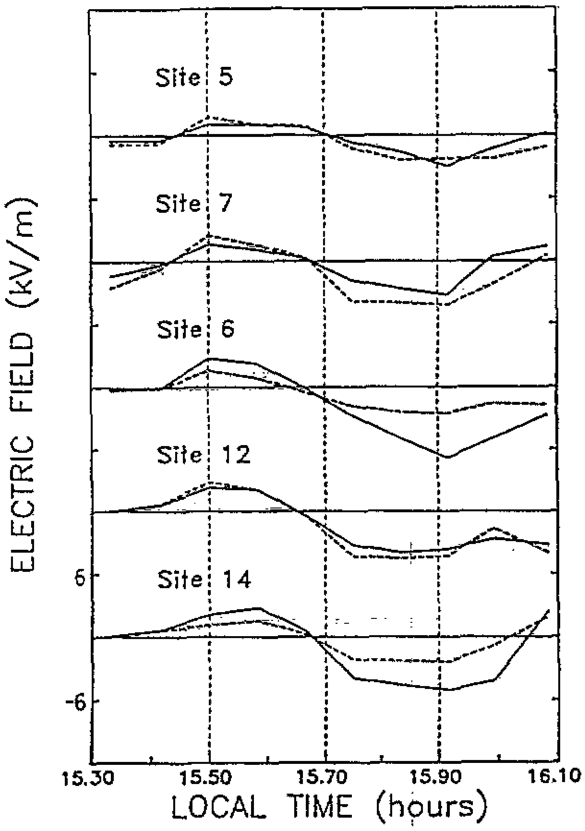

Fig. 3A Time series of the field mill (dashed line) and co-located corona (solid line) measurements during a thunderstorm. This figure is for Sites 5, 7, 6, 12 and 14 in the northern half of the array. Differences are caused by space charge as discussed in the text. These time series were used to plot the electric field contours shown in Figs. 4 through 7.

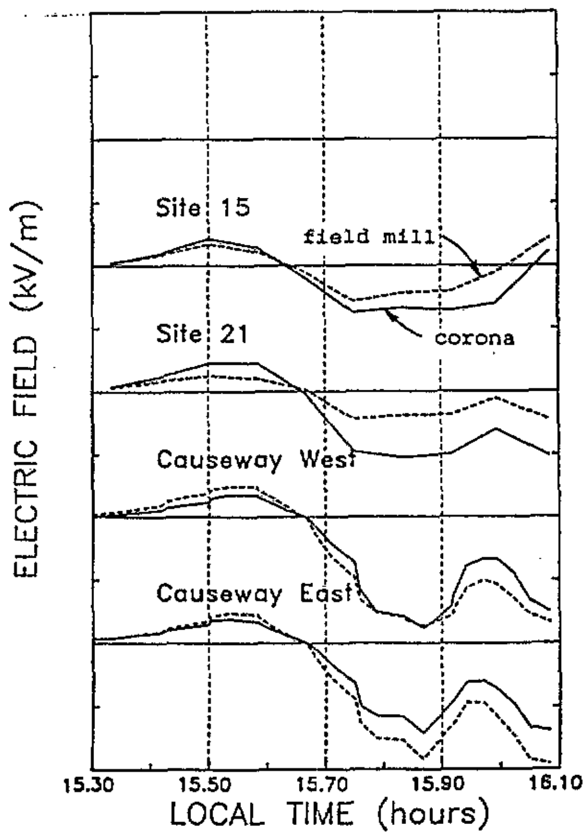

Fig. 3B The same as Fig. 3A for Sites 15, 21, Causeway West and Causeway East in the southern half of the array. Note the close proximity of Site 21, which is about 200 meters inland from the shoreline, relative to the causeway sites which are essentially surrounded by water. Electric field contours pack in at this interface for reasons discussed in the text.

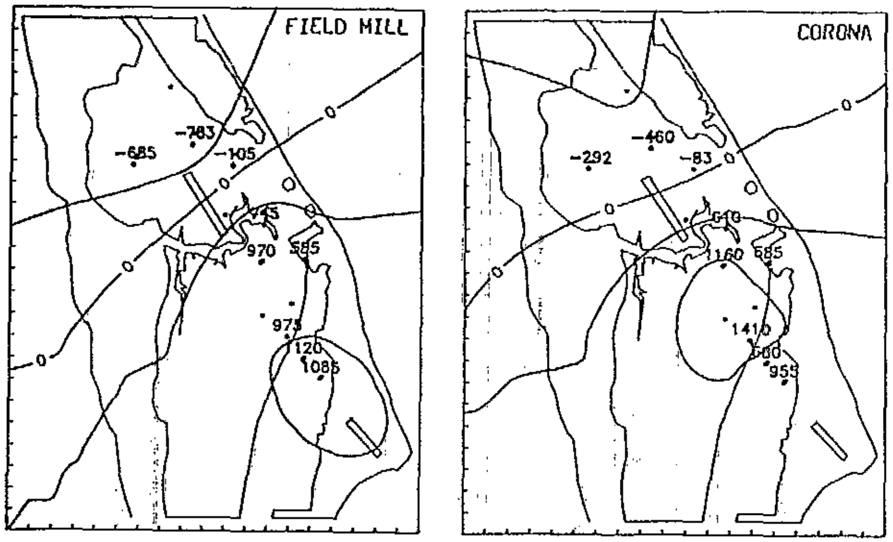

Fig. 4 Field mill and corona contours at 1525 EDT, 3 October 88.

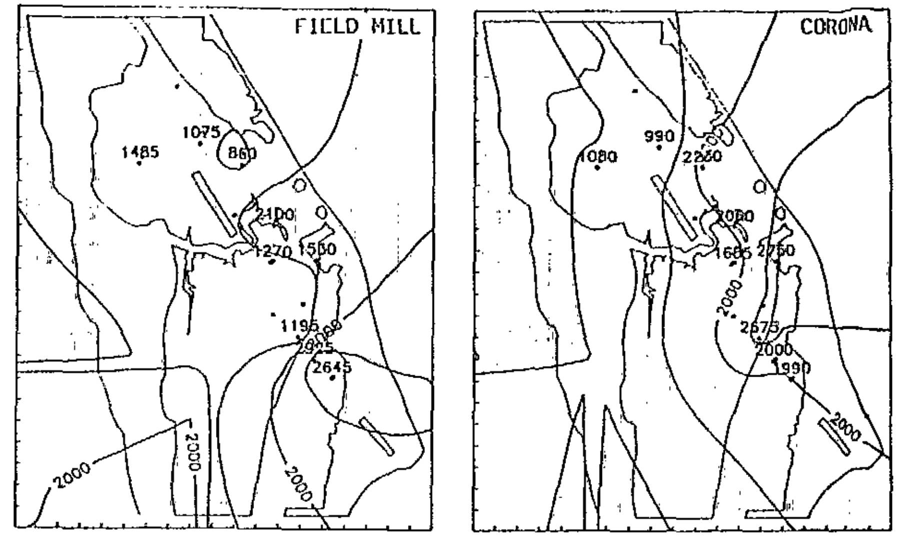

Fig. 5 Field mill and corona contours at 1535 EDT, 3 October 88.

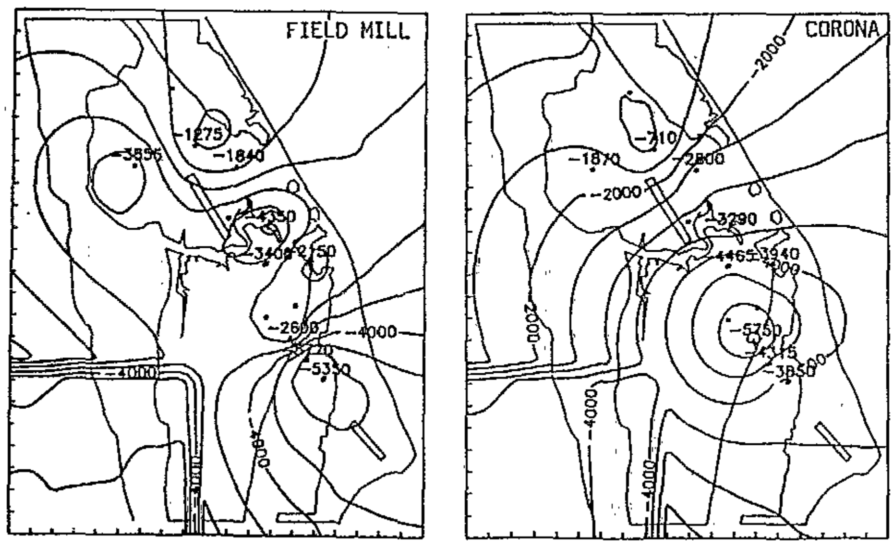

Fig. 6 Field mill and corona contours at 1545 EDT, 3 October 88.

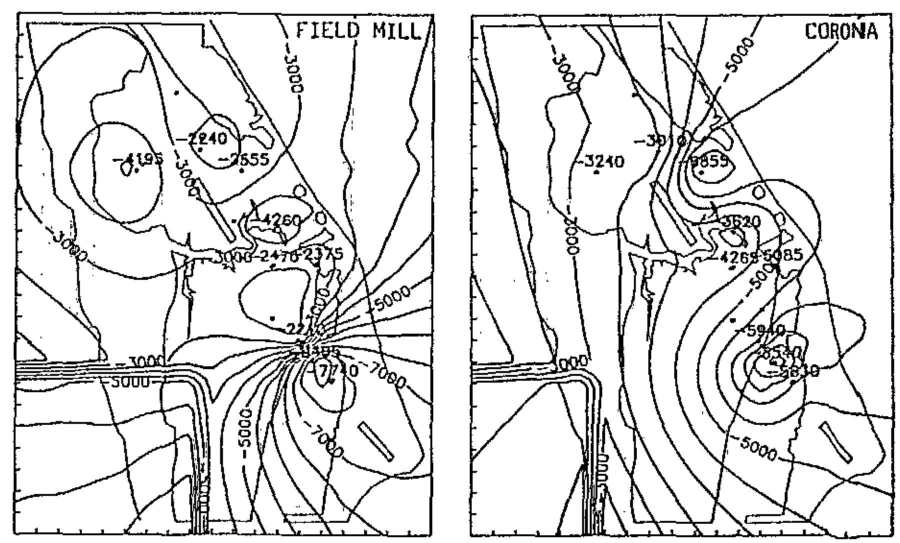

Fig. 7 Field mill and corona contours at 1555 EDT, 3 October 88.

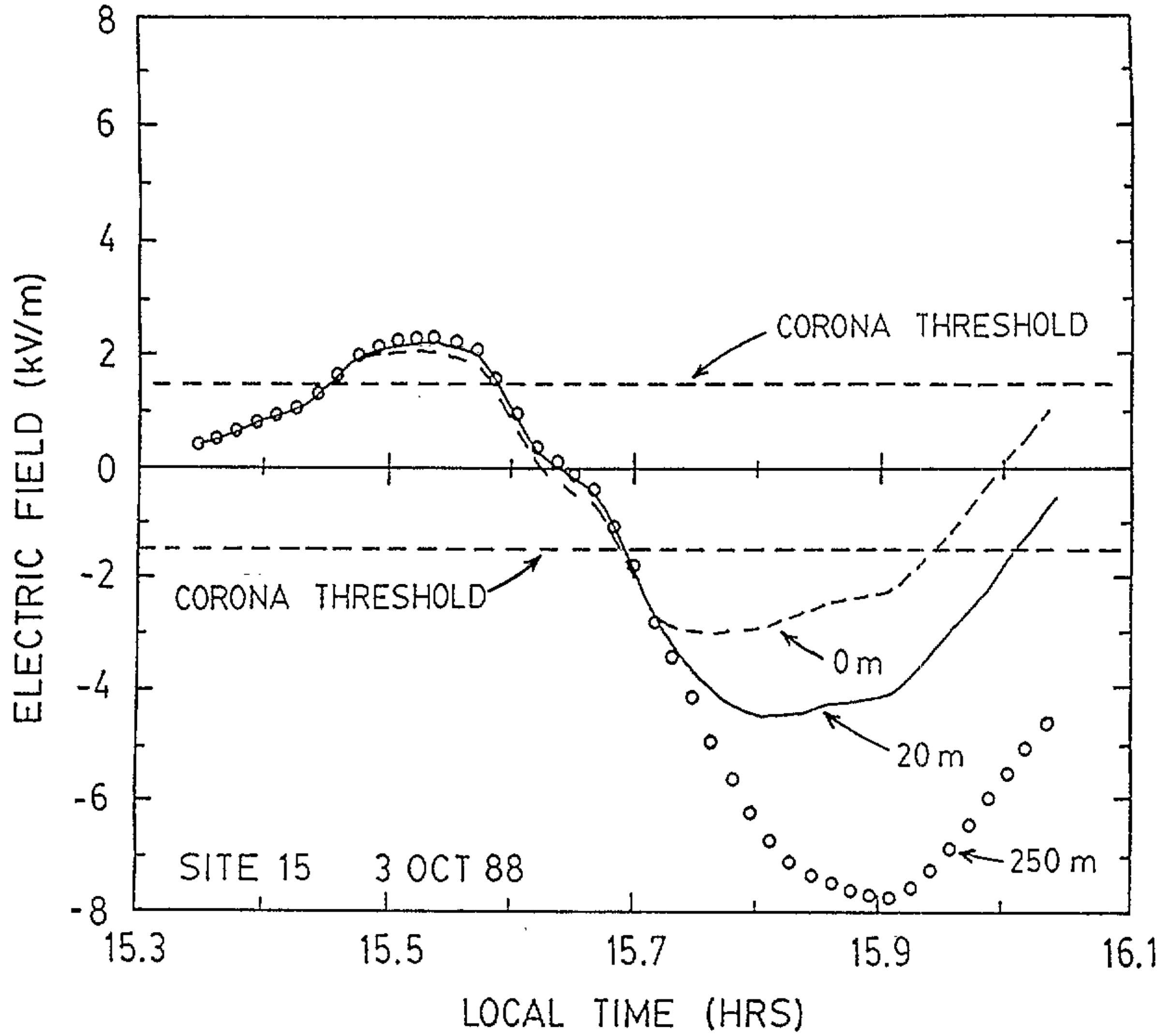

Fig. 8 Results of running the model with data from Site 15 on land. During the initial positive swing the surface field barely exceeded the assumed corona threshold and there was little affect due to corona on fields aloft. The subsequent negative swing exceeded the corona threshold and the space charge effects become apparent. The computed peak fields at 20 meters and 250 meters were -4 kV/m and -8 kV/m respectively. Assuming that the fields over the causeway derived from the 20 meter corona points approximate conditions above the space charge, the maximum negative fields of -8 to -10 kV/m are in agreement with the model prediction. This is the only test of the model that has been possible since only one thunderstorm period has been observed with the combined corona and field mill arrays.

PORTABLE COMBINED OPTICAL AND ELECTRIC FIELD CHANGE INTRACLOUD LIGHTNING DETECTOR

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Weston, MA 02193
(617)899-1834

BACKGROUND

Optical lightning detection has been used at research institutes for years and movie cameras equipped with optical lightning detectors were operated by astronauts on several Space Shuttle missions to detect lightning in clouds within the field of view during daylight and at night. The optical lightning detector reported here is the first such device available commercially. The addition of a flat plate antenna section, which responds to electric field changes, provides the advantages of both types of detectors in a single compact unit. Flat plate antenna sensors also have not been available as an inexpensive commercial product in the past. By combining both signals in a coincidence circuit false alarms are essentially eliminated.

OPTICAL LIGHTNING DETECTION

Lightning emits optical signals which in some respects are easier to detect and interpret and more reliable indicators than longer wavelength electromagnetic radiation. In daylight, depending on background light intensity, cloud-to-ground lightning can be observed visually, but intracloud lightning is rarely seen. At night the human eye sees essentially all lightning from clouds within the field of view. The optical lightning detector provides close to nighttime visual sensitivity during daylight. Intracloud lightning in the upper portion of brightly sunlit clouds is sensed as easily as cloud-to-ground discharges. The optical lightning detector offers some important advantages over other types of lightning detection including:

-- ability to report intracloud lightning
-- close to 100% detection efficiency within about 20 km or further (depending on visibility)
-- can determine if specific clouds contain lightning
-- low cost (less than 1% of mapping systems)
-- no installation or maintenance
-- no requirement for AC power
-- no requirement for communications between remote sensors and central processor
-- reliability
-- portability
-- simplicity of operation

The limitations of an optical detector are:

-- does not provide range
-- azimuth may be inaccurate if light is reflected from other clouds
-- nearby clouds or rain can block view of more distant lightning (but flat plate antenna will sense them)

INDUCTION FIELD CHANGE LIGHTNING DETECTION

The current second generation optical lightning detector includes a flat plate field change detector in order to improve performance. The antenna is the shiny metal plate on the end of the instrument. This section can be operated independently or in coincidence with the optical section. Improvements include:

-- coincidence mode: elimination of false optical signals which can occur from reflections off raindrops or other objects or from windows within buildings

-- field change mode: ability to detect distant lightning when optical visibility is obstructed

-- omnidirectional (no need to aim instrument at clouds)

Electric field change detection has been selected as the best way to use non-optical emissions, rather than "sferics" type emissions such as one hears on an AM radio. The problem with using radio static signals for lightning detection is that such signals decrease slowly (1/R) with distance in the far field and are reflected from the ionosphere. Thus they propagate for long distances; one has no idea if the flashes are nearby or a few hundred miles away. If range is purposely limited by reducing sensitivity, only the more energetic cloud-to-ground flashes are received and the earlier intracloud discharges are missed. However, by sensing VLF field changes in the "near field" where signal intensity decreases rapidly with distance ($1/R^3$), one can eliminate reception of distant signals without decreasing sensitivity for nearby flashes.

Use of this flat plate antenna section makes it possible to survey for lightning for about 50 km in all directions on days with limited visibility without having to point the detector at specific clouds. Such omnidirectional sensing can be done before there are any nearby visible clouds. It is best to use this mode outdoors since electric signals are screened from the interior of buildings with metal structure.

When threatening clouds appear, the instrument can be switched to the "optical" or "both" (coincidence) mode to see if these clouds contain lightning. In any of the three operational modes the unique staccato sound signature characteristic of lightning (caused by the strokes within each flash) can be heard; this is useful for distinguishing lightning from any noise sources.

DISTANCE TO LIGHTNING

In the early part of a storm, when lightning is occurring only once every few minutes or a few times per minute -- so that individual flashes (beeps from the instrument) can be associated with subsequent thunder -- it is possible to determine the distance to the discharge. This classic "flash to bang" method works because sound travels 1 mile in 5 seconds. The technique is useful for distances up to about 8 km, or possibly as much as 15 km on occasion, depending on sound propagation and lightning frequency.

RANGE

The detector's range is essentially line-of-sight. However, it is capable of picking up lightning from clouds behind those in the foreground because of light transmission through the thin veil of high cirrus clouds which is often present near thunderstorms. Thus, the range is not usually restricted to the closest clouds and it is on the order of 50 km with other clouds between the source and detector. The range can be as much as 150 km in clean air with no clouds between the detector and clouds with lightning.

CIRCUIT FEATURES

The accompanying block diagram shows the components of the circuitry. A highpass filter and bandpass filter restrict signals essentially to lightning (and strobe lights when operated in the purely optical mode). The detection threshold automatically adjusts to a level just below that of the variable background light intensity to maximize sensitivity. The timing diagram illustrates how the optical and field change sections trigger when the threshold is exceeded and how the signal is maintained for 50 ms to aid in hearing the pulses (strokes). This diagram illustrates how both signals must be on for the coincidence circuit to respond.

PHYSICAL SPECIFICATIONS

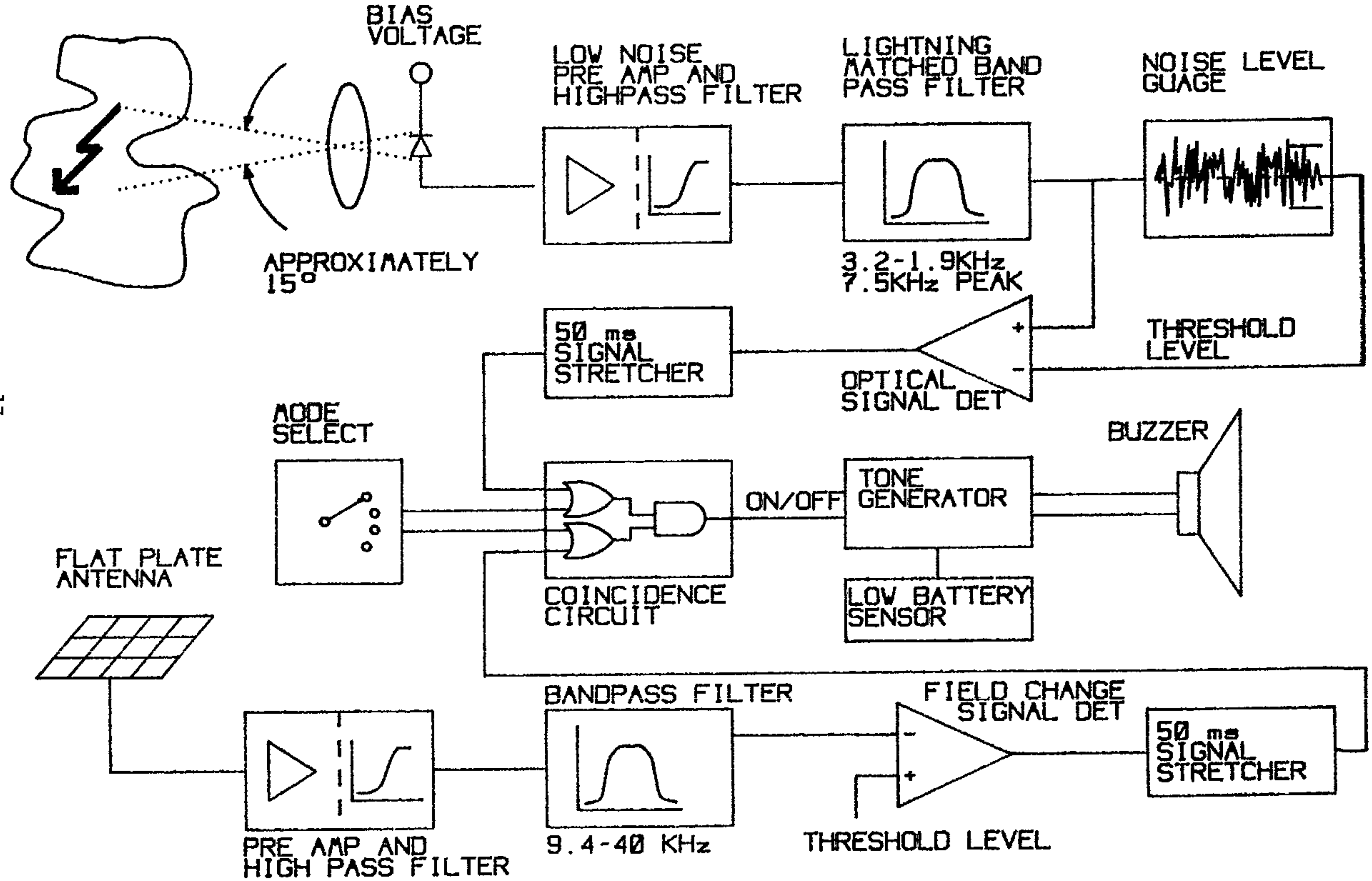
The M-10 dimensions are 18 cm (7.0 in) x 10 cm (3.8 in) x 3.5 cm (1.3 in). It weighs 450 gm (1 lb). A fitting in the base allows it to be mounted on a camera tripod so it can easily be pointed toward suspicious clouds without having to hold it in position by hand for an extended period of time. (It also can be supported by any convenient object.) It can be heard 20 meters away when background noise is low. The instrument is powered by two 9 volt alkaline transistor batteries which are inserted into molded housings when the back plate is removed. The detector beeps every 3 seconds when the batteries need replacement.

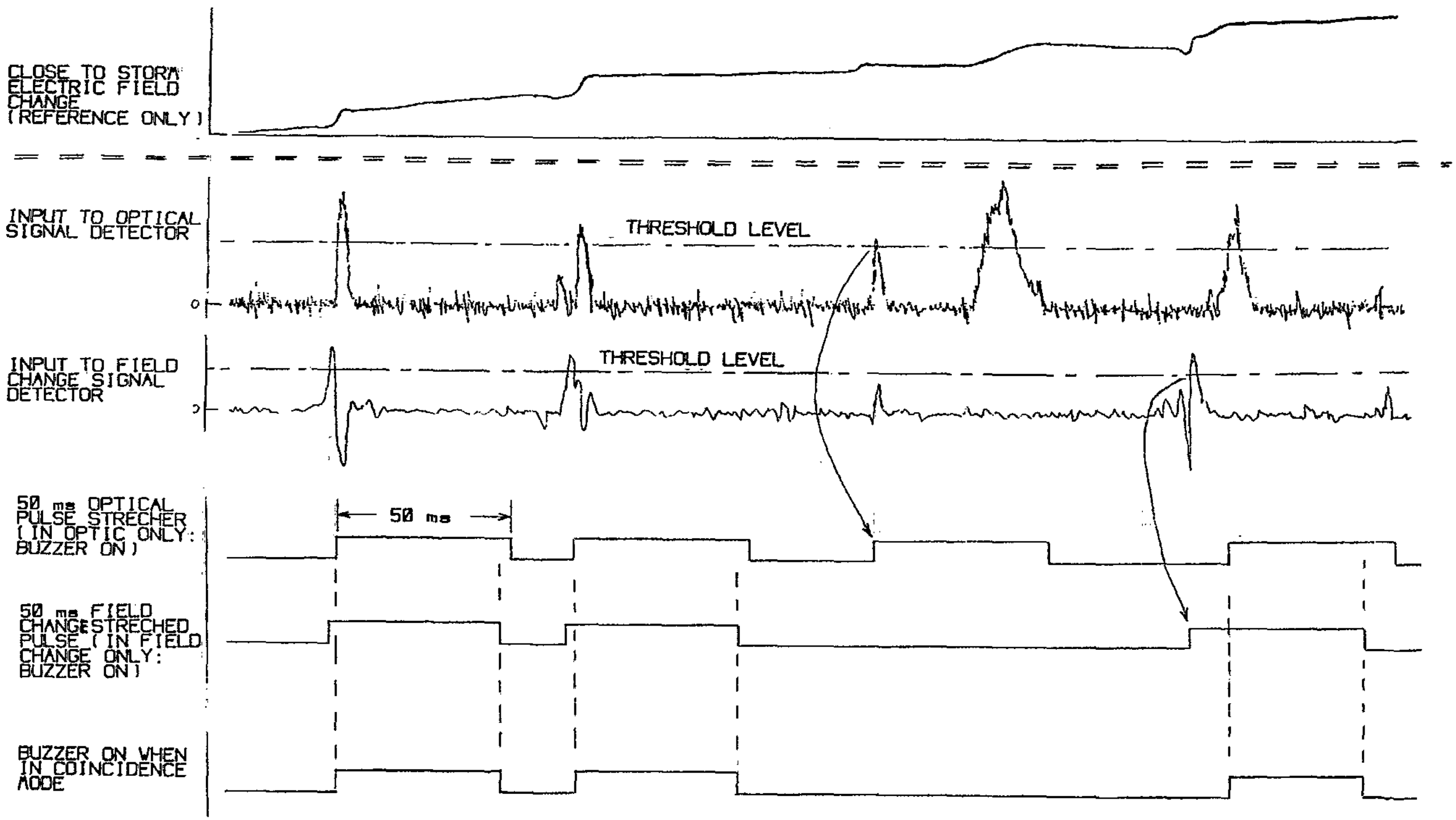
APPLICATIONS

To date over 100 optical lightning detectors are being used at universities and golf courses as well as government laboratories and field test sites. A half dozen observers covering the KSC test area could tell with 100% reliability if any visible clouds over or near the region contained any kind of lightning.

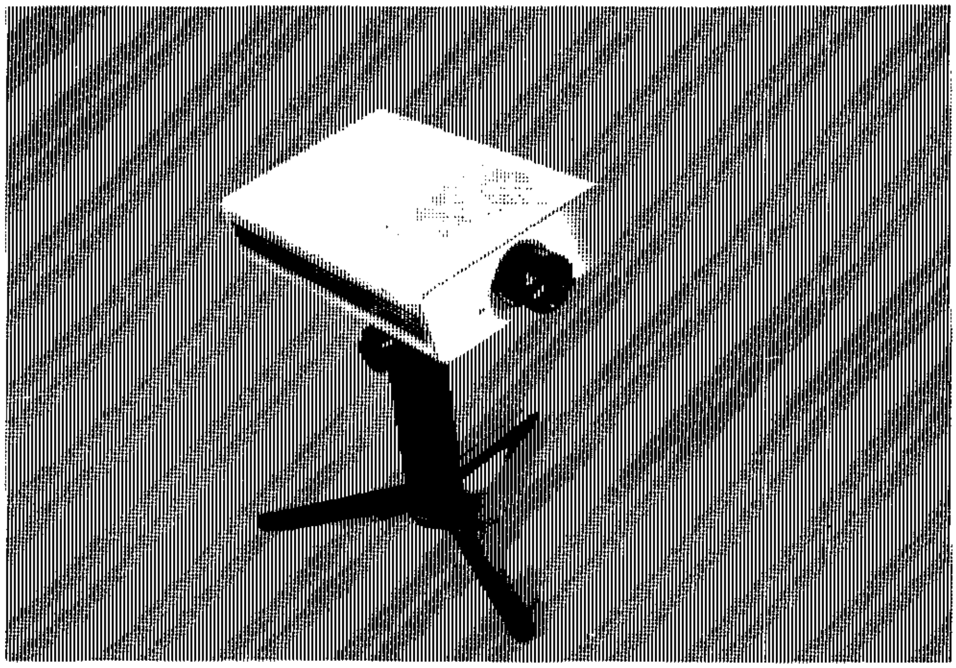
The instrument also works on aircraft when propeller reflections are eliminated. Presently a system is being developed for aircraft use. The instrument also detects strobe lights and will be used also for collision avoidance.

M-10 BLOCK DIAGRAM





M-10 LIGHTNING DETECTOR: OPTICAL AND FIELD CHANGE CONTROL OF BUZZER TIMING



LIGHTNING SURVEILLANCE INSTRUMENTATION AT THE EASTERN TEST RANGE (ETR)

Michael W. Maier
Operational Analysis Section
Computer Sciences Raytheon (CSR)

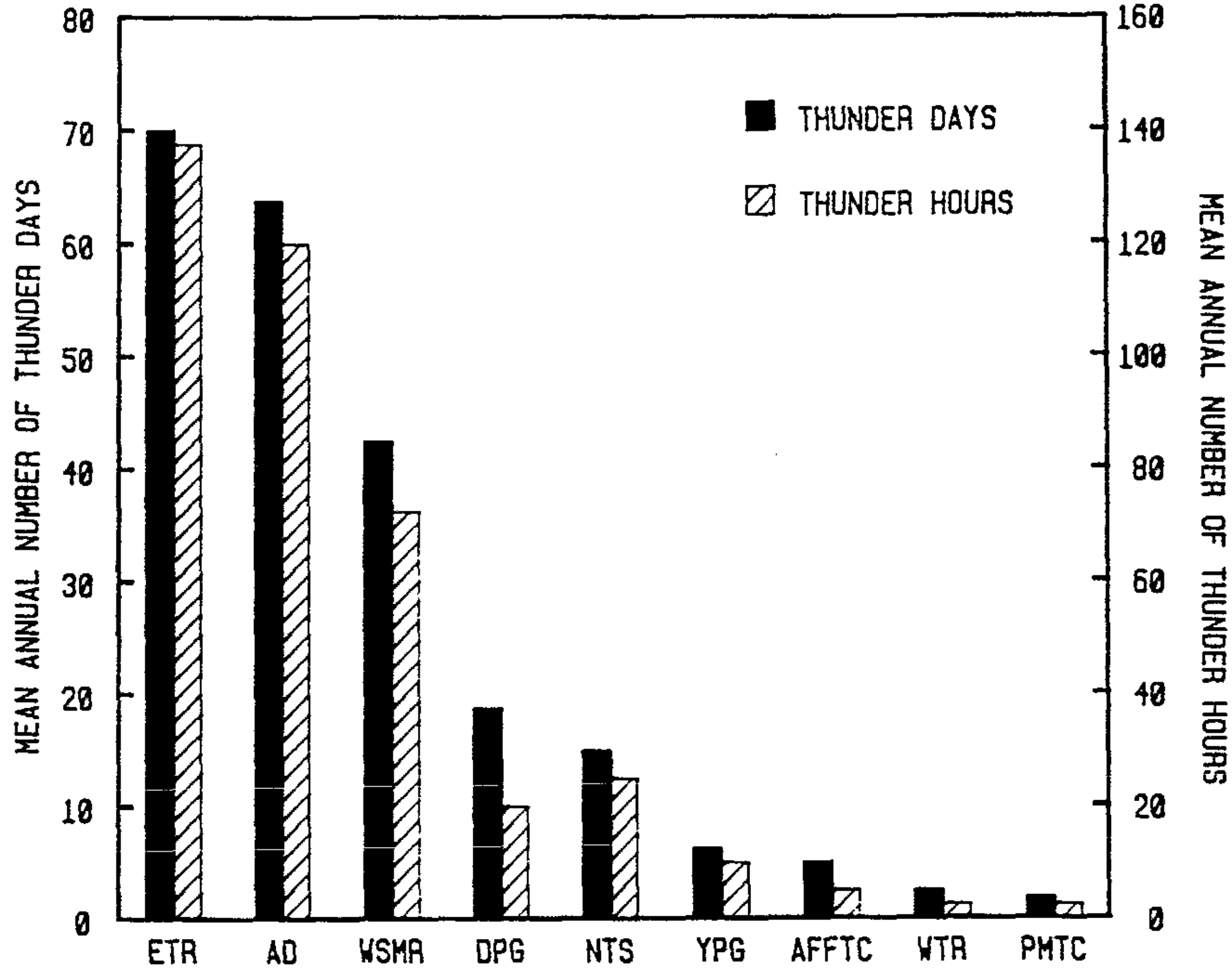
Presented on behalf of:

ESMC Staff Meteorologist
(Air Weather Service DET 11, 2WS)
Patrick Air Force Base, Florida

Overview

- Background
- Launch Pad Lightning Warning System (LPLWS)
  - Present configuration.
  - Planned configuration.
- Cloud-to-Ground Lightning Surveillance System (LLP)
  - Present configuration.
  - Performance to date.
  - Planned Configuration.
- Lightning Detection and Ranging System (LDAR)
  - Planned configuration.
- Airborne Field Mill Program (ABFM)

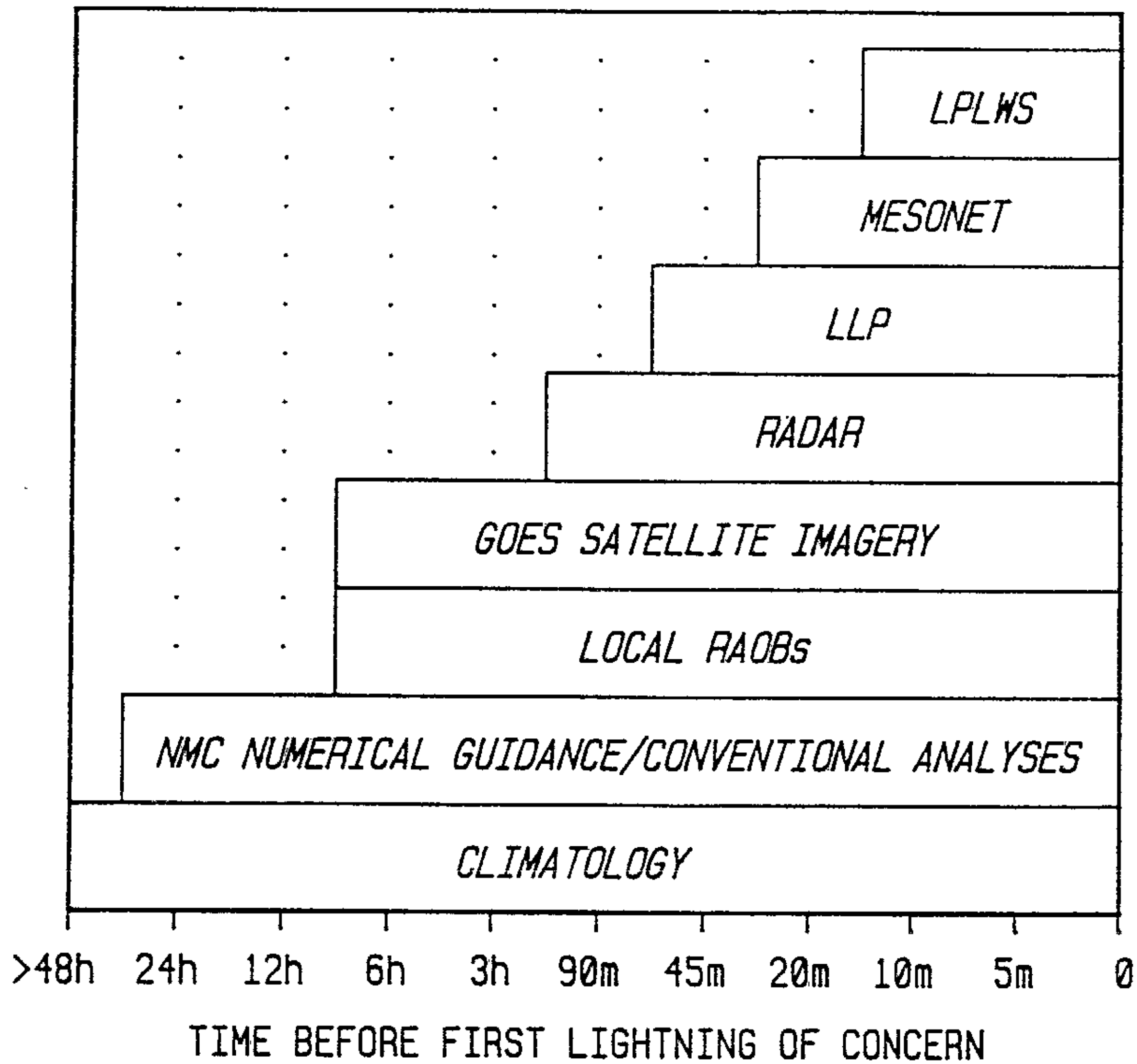
THUNDERSTORM INCIDENCE AT SELECTED TEST RANGES

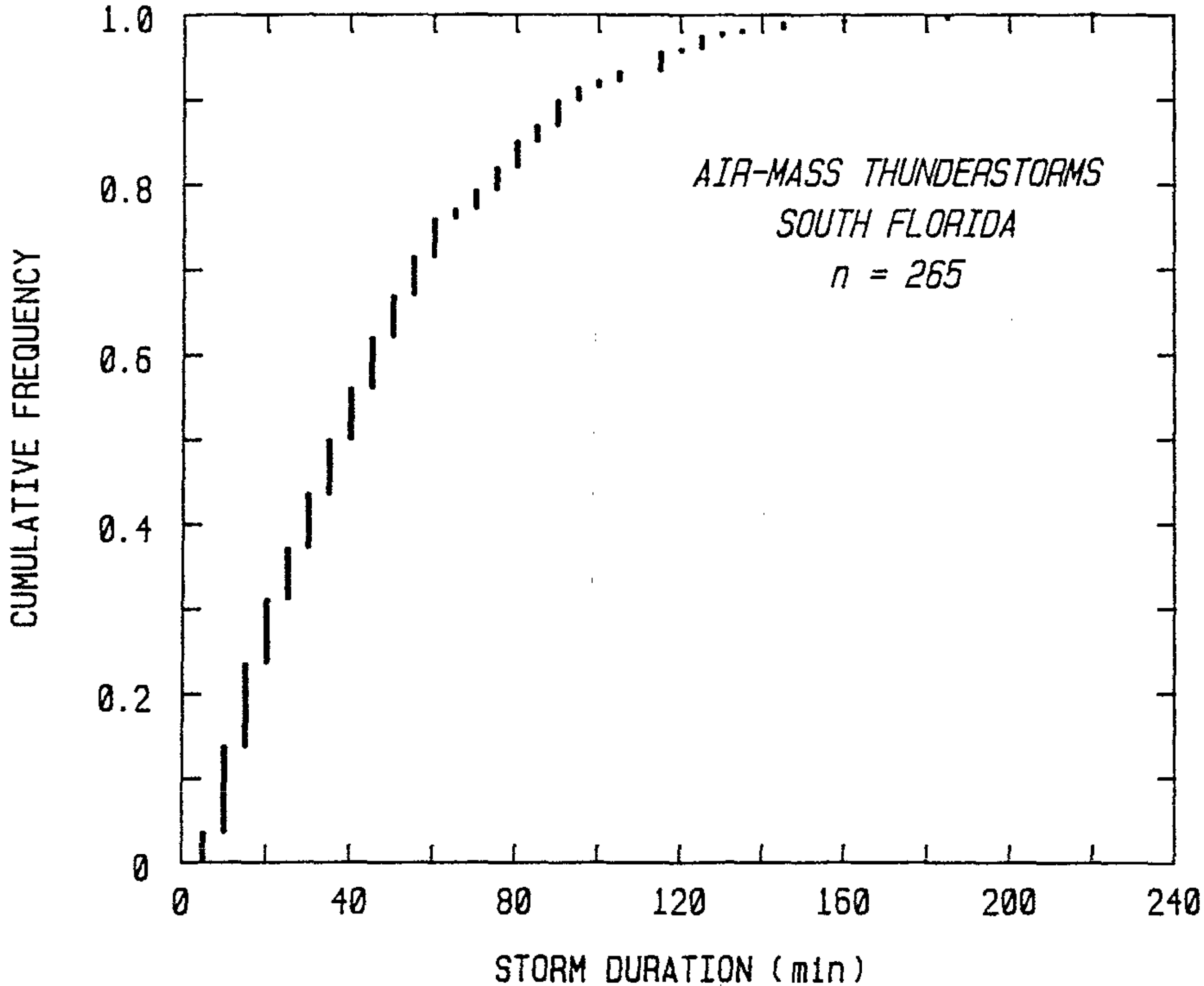


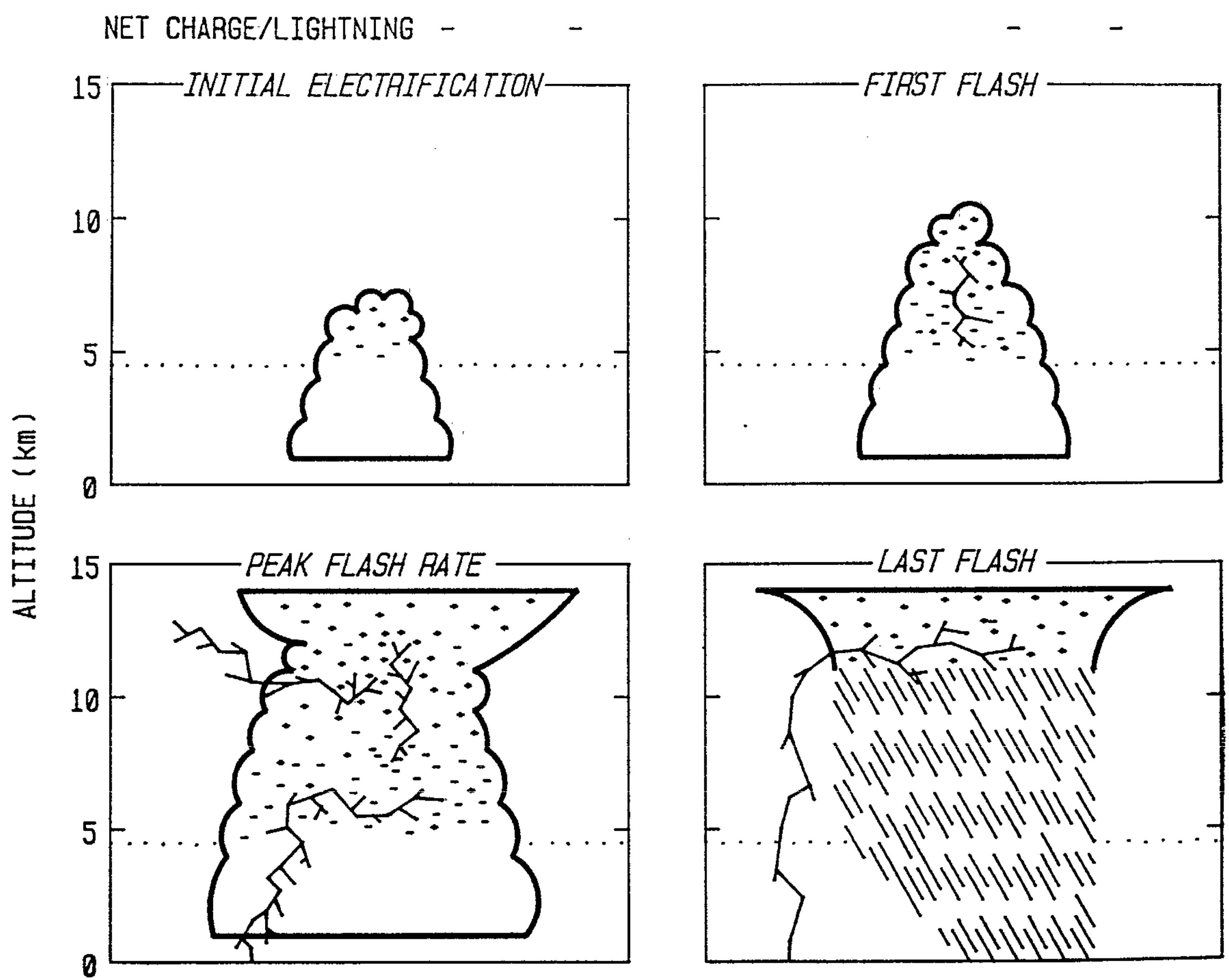
Requirements and Applications

- Evaluation of Lightning Launch Commit Criteria.
- Evaluation of Lightning METWATCH Criteria.
- Lightning Incident Evaluation.
- Lightning Threat Climatologies.
- Forecast/Warning Technique Development and Verification.

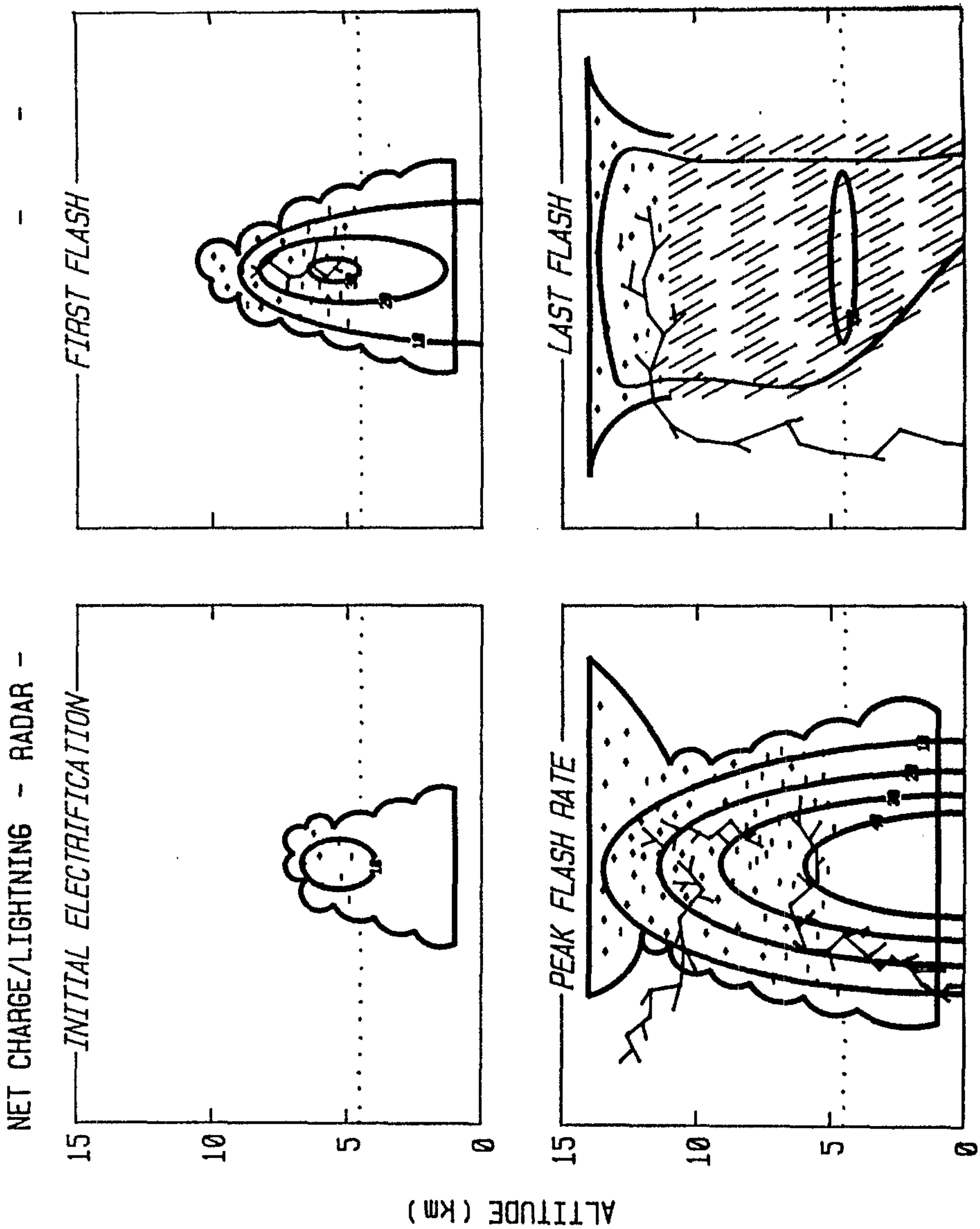
CSR

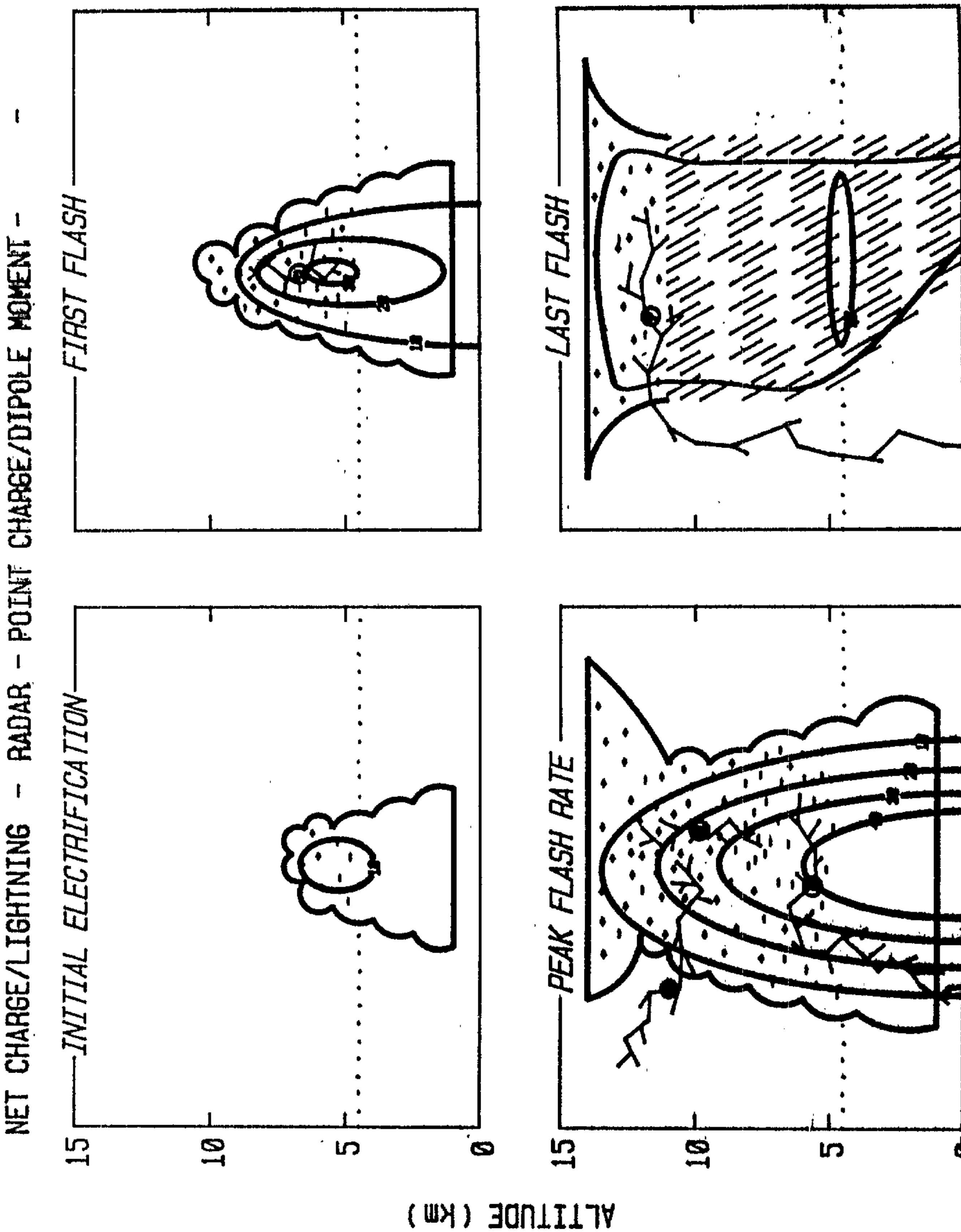

LPLWS
MESONET
LLP
RADAR
GOES SATELLITE IMAGERY
LOCAL RAOBs
NMC NUMERICAL GUIDANCE/CONVENTIONAL ANALYSES
CLIMATOLOGY
>48h 24h 12h 6h 3h 90m 45m 20m 10m 5m 0
TIME BEFORE FIRST LIGHTNING OF CONCERN


AIR-MASS THUNDERSTORMS
SOUTH FLORIDA
n = 265
CUMULATIVE FREQUENCY
1.0
0.8
0.6
0.4
0.2
0
0
40
80
120
160
200
240
STORM DURATION (min)



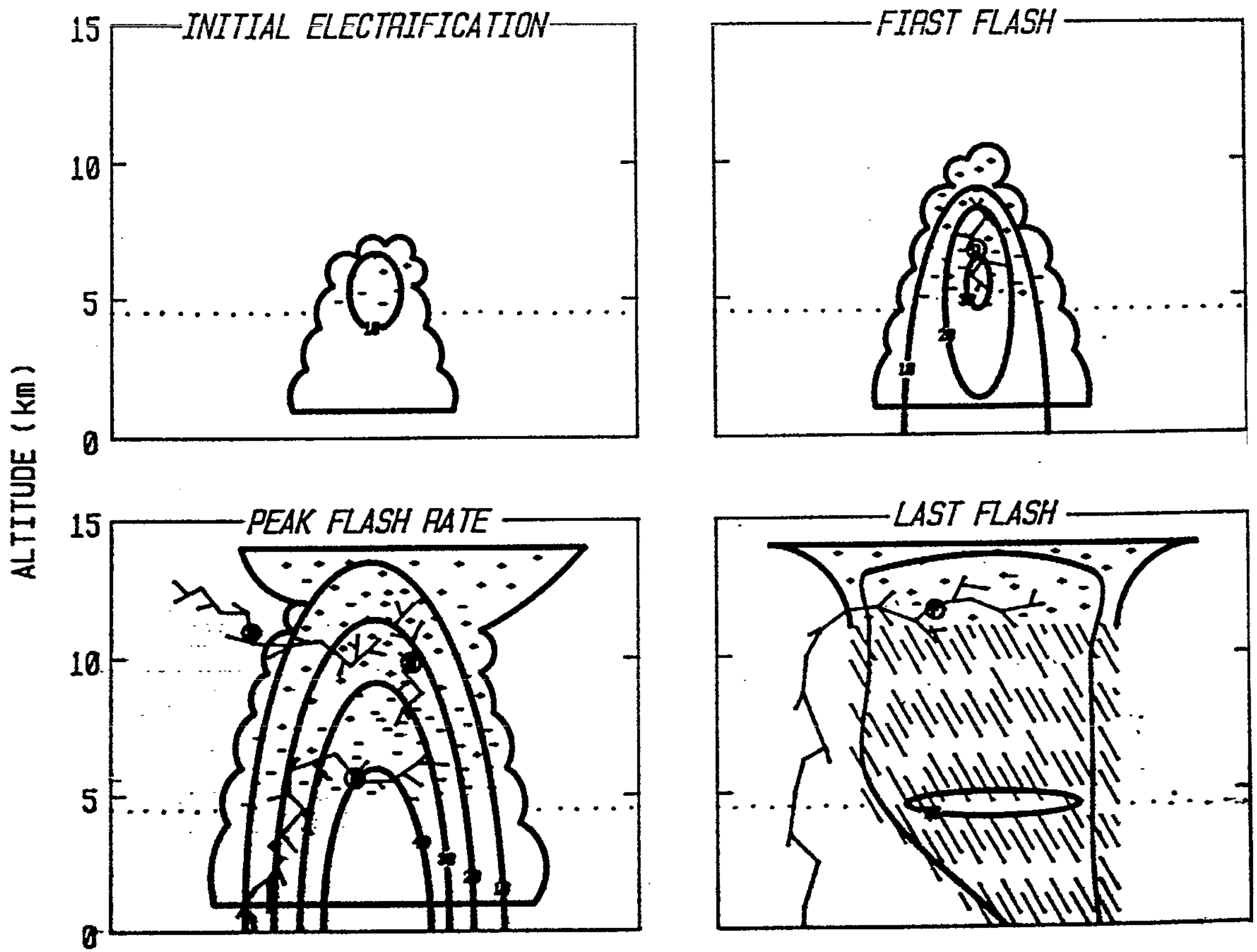
NET CHARGE/LIGHTNING - - - -
INITIAL ELECTRIFICATION
FIRST FLASH
PEAK FLASH RATE
LAST FLASH
ALTITUDE (km)
15
10
5
0


NET CHARGE/LIGHTNING - RADAR -
INITIAL ELECTRIFICATION
FIRST FLASH
PEAK FLASH RATE
LAST FLASH
ALTITUDE (km)
15
10
5
0

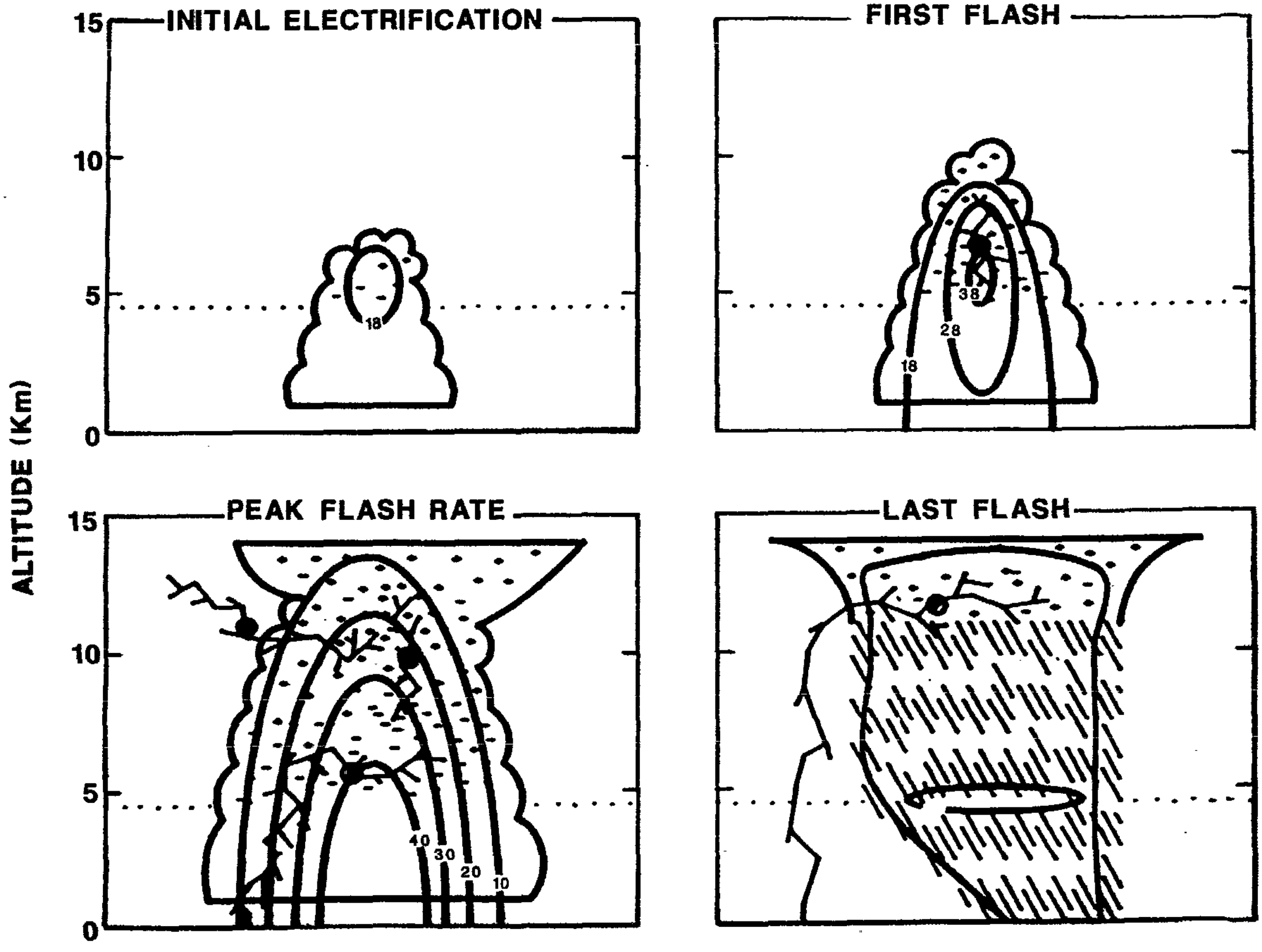


NET CHARGE/LIGHTNING - RADAR - POINT CHARGE/DIPOLE MOMENT -
INITIAL ELECTRIFICATION
FIRST FLASH
PEAK FLASH RATE
LAST FLASH
ALTITUDE (km)
15
10
5
0

NET CHARGE/LIGHTNING - RADAR - POINT CHARGE/DIPOLE MOMENT -

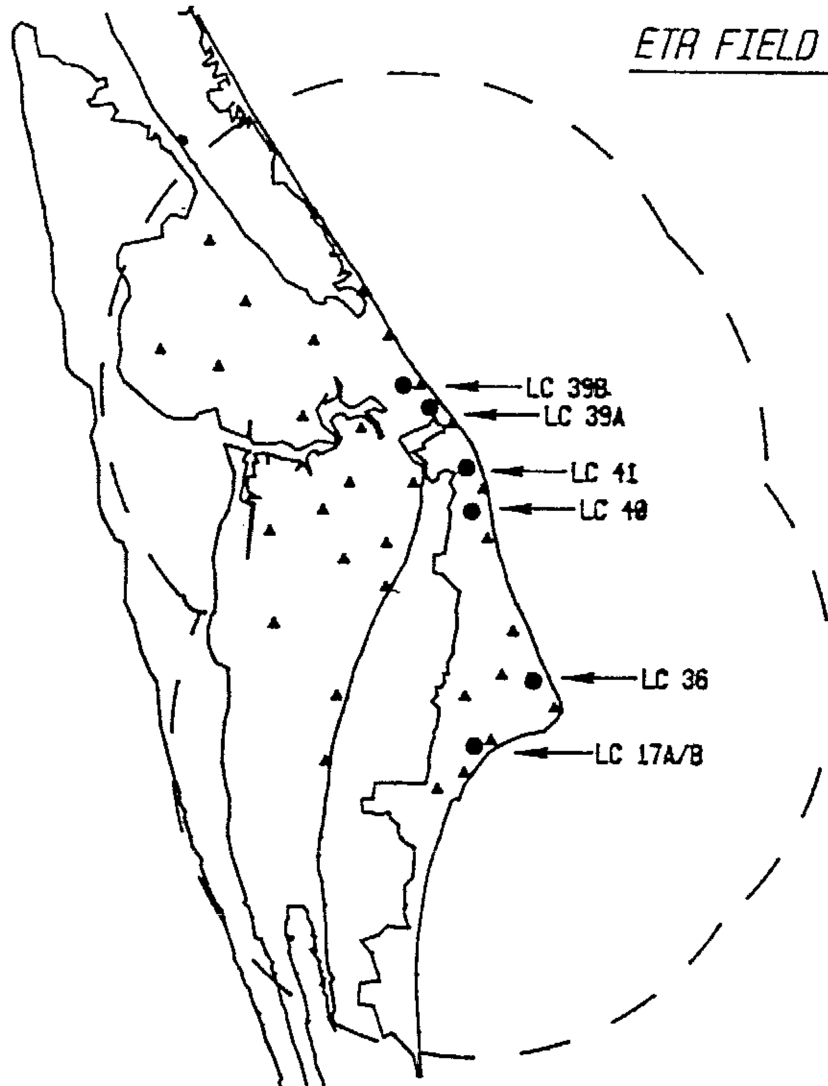


NET CHARGE/LIGHTING - RADAR - POINT CHARGE/DIPOLE MOMENT - LLP - LDAR

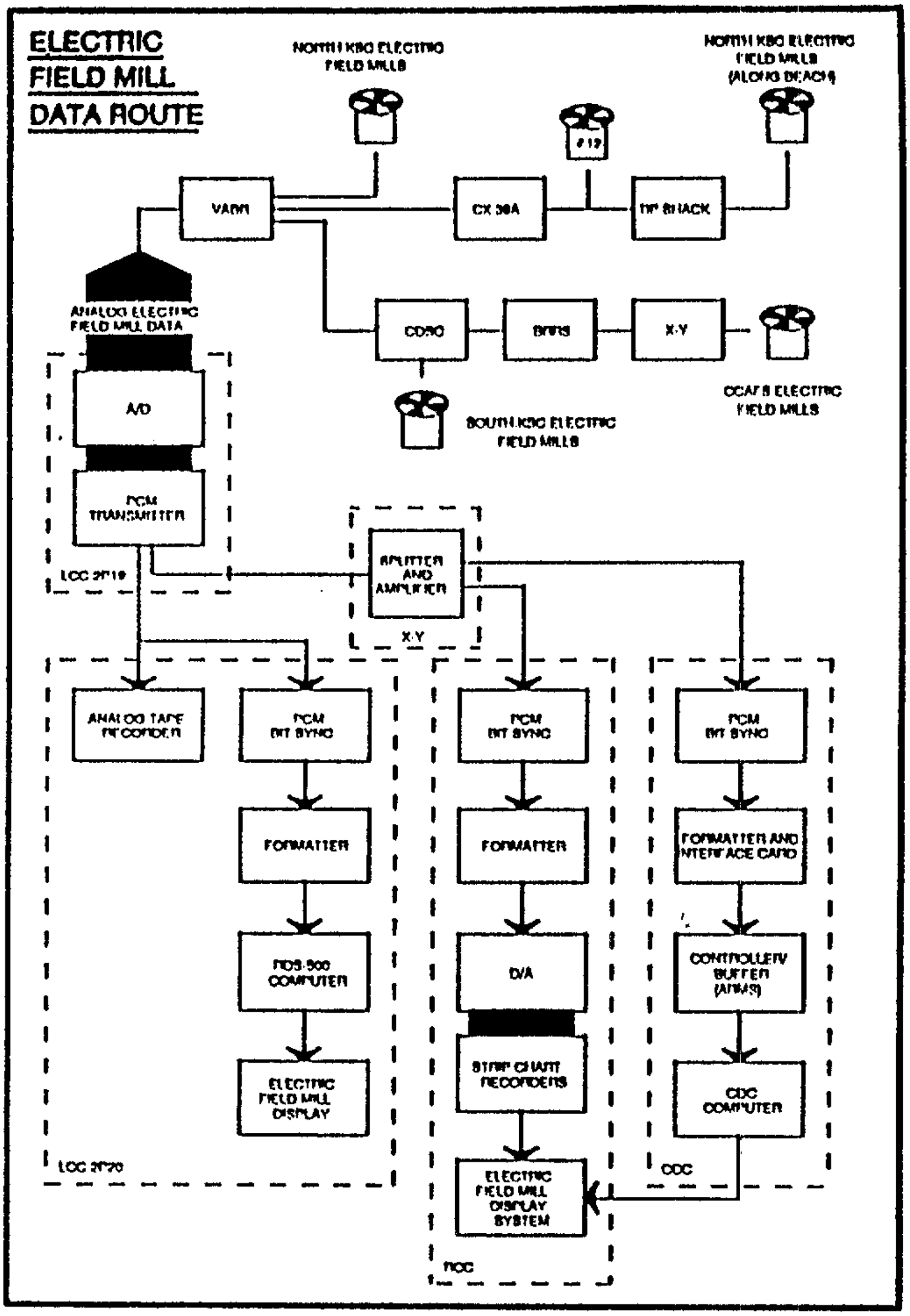


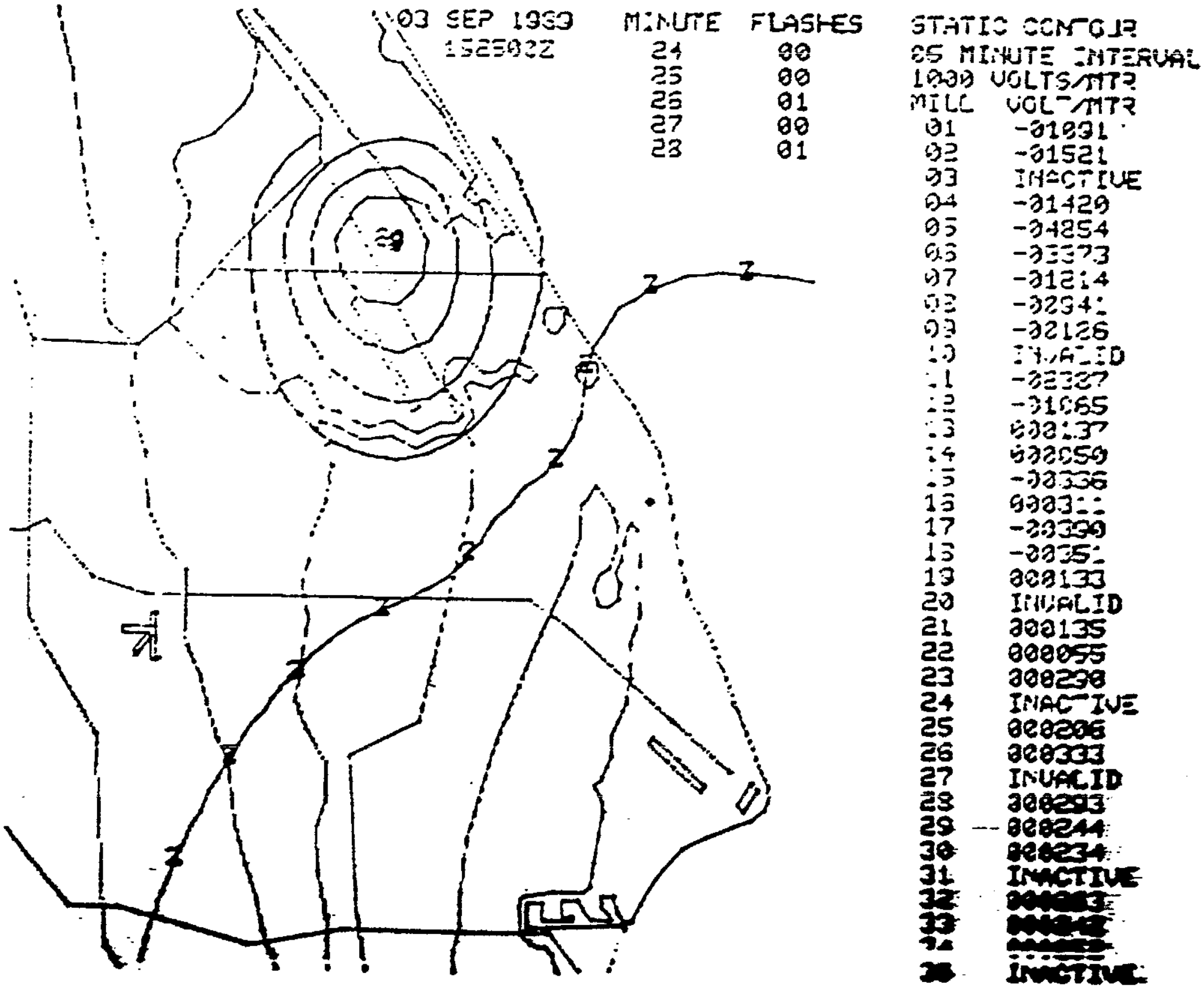
Launch Pad Lightning Warning System
(LPLWS)

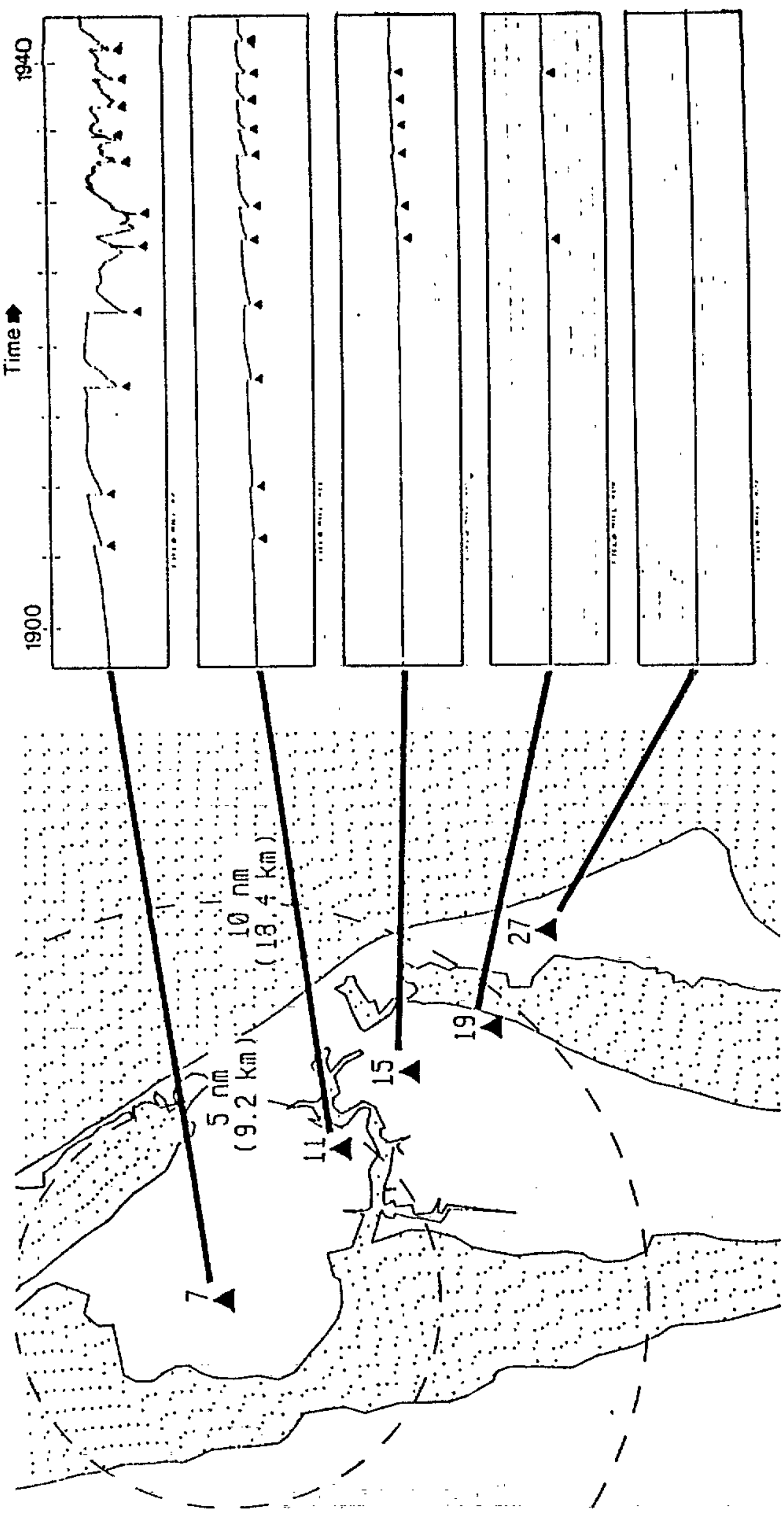
ETR FIELD MILL NETWORK (LPLWS)



CSR


ELECTRIC
FIELD MILL
DATA ROUTE
ANALOG ELECTRIC FIELD MILL DATA
A/D
PCM TRANSMITTER
SPLITTER AND AMPLIFIER
X-Y
SOUTH KSC ELECTRIC FIELD MILLS
ANALOG TAPE RECORDER
PCM BIT SYNC
FORMATTER
ELECTRIC FIELD MILL DISPLAY
PCM BIT SYNC
FORMATTER
D/A
STRIP CHART RECORDERS
ELECTRIC FIELD MILL DISPLAY SYSTEM
PCM BIT SYNC
FORMATTER AND INTERFACE CARD
CDC COMPUTER
CDC


03 SEP 1989
152500Z
MINUTE FLASHES
24 00
25 00
26 01
27 00
28 01
STATIC CONTOUR
05 MINUTE INTERVAL
1000 VOLTS/MTR
MILL VOLT/MTR
01 -01091
02 -01521
03 INACTIVE
04 -01420
05 -04254
06 -03373
07 -01214
08 -02341
09 -02126
10 INVALID
11 -02327
12 -01065
13 000137
14 000050
15 -00336
16 000311
17 -00390
18 -00351
19 000133
20 INVALID
21 000135
22 000055
23 000298
24 INACTIVE
25 000206
26 000333
27 INVALID
28 000293
29 000244
30 000234
31 INACTIVE
32
33
34
35 INACTIVE



Time
1900
1940
7
11
15
19
27
5 nm
(9.2 km)
10 nm
(18.4 km)

LPLWS UPGRADE PROGRAM

- Replace existing sensors with new sensors (NASA/MSFC).
  - Inverted shutter design.
  - Digital output.
  - Self calibrating.
  - Remote diagnostic capability.
  - Increased dynamic range.
  - Low noise, brushless DC motor.
  - Dual channel capability for calibration.

- Replace CYBER sub-system with dedicated host computer.
  - Increase throughput.
  - Decreased processing delays.
  - Increased system availability.
  - Improved reduction algorithms.

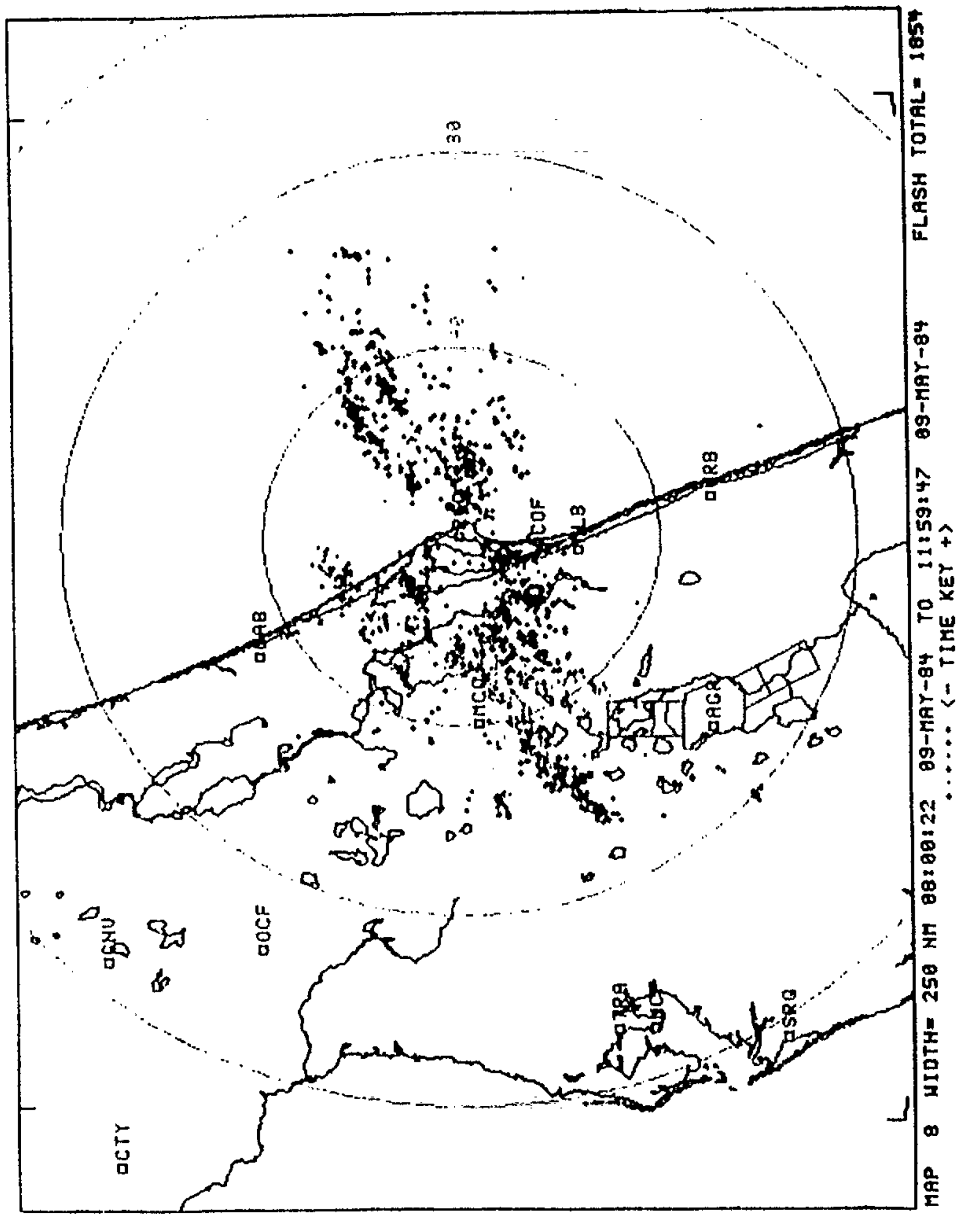
- Replace monochrome CRT displays with color workstations.
  - Higher screen resolution.
  - Improved basemap resolution.
  - Enhanced user interface.
  - Alarms.

Related Support Initiatives

- Field mill users manual has been developed (ESMC/NASA).
- Absolute sensor and site calibration program (ESMC/NASA).
- Relationship between surface fields and lightning strike probability being investigated (NASA/KSC).
- An expert system field mill data analyst is under development (NASA/KSC).

CSR

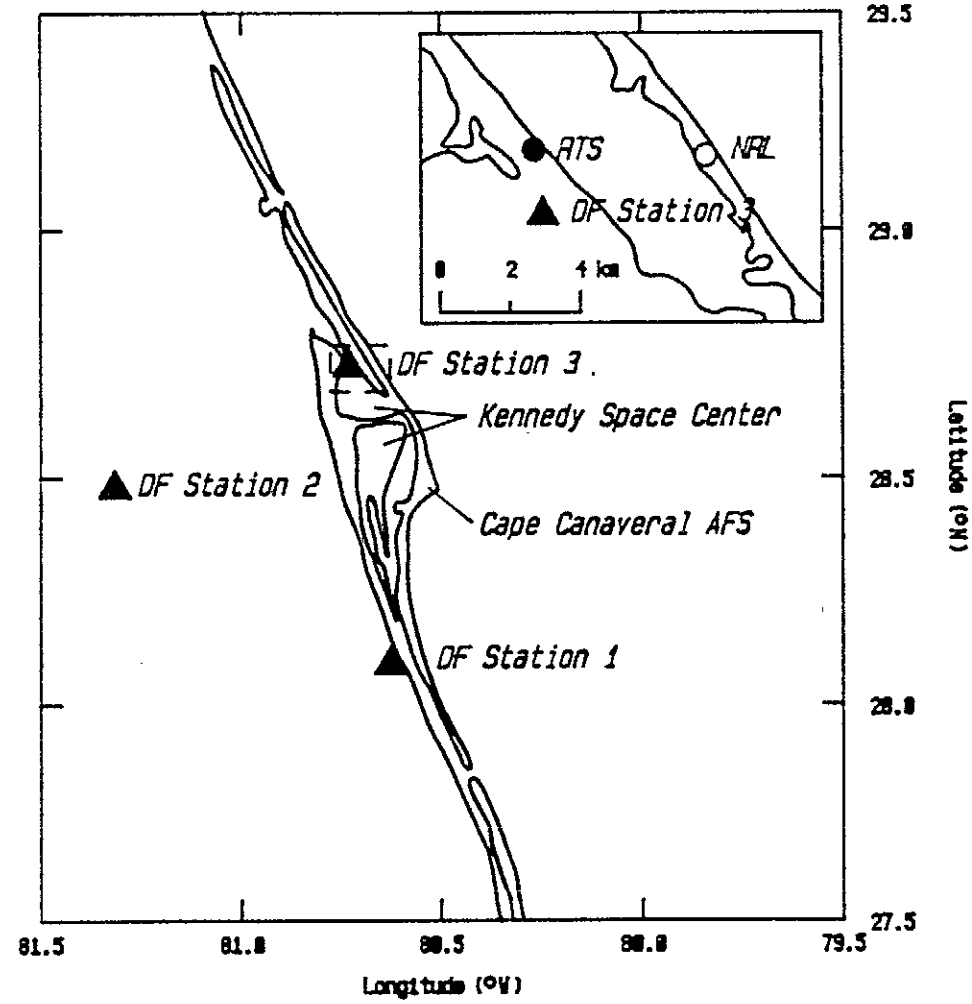
Cloud-Ground Lightning Surveillance System (LLP)


MAP 8 WIDTH= 250 NM 08:00:22 09-MAY-84 TO 11:59:47 09-MAY-84 FLASH TOTAL= 1854
...... <- TIME KEY +>
CTY
GNV
OCF
DAB
MCO
COF
MLB
VRB
AGR
TPA
SRQ
33

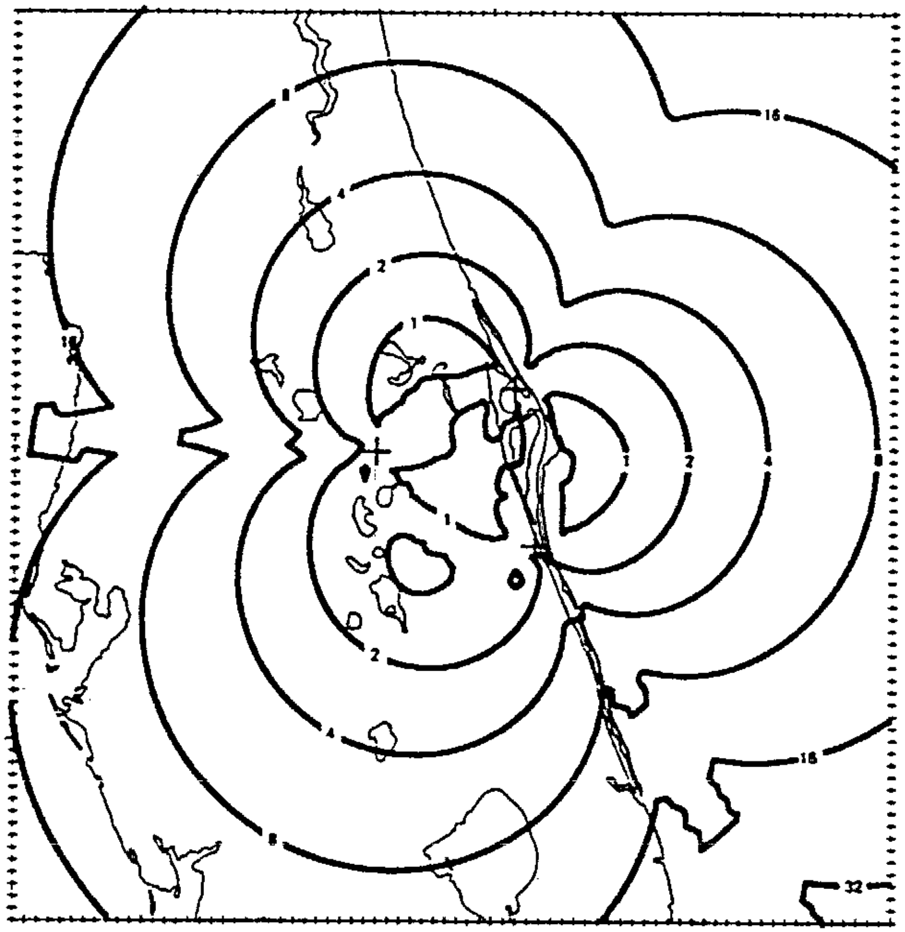
ETR LLP CAPABILITIES	Present System		Upgraded System
	Med Gain	Low Gain	
SENSORS			
Number	3	2	5
Type	DF 80-02	DF 80-02	ALDF
Gain	Medium	Low	Low
Average Baseline	65 km	15 km	40 km
Positive Stroke Det.	No	Yes	Yes
SYSTEM			
Effective Range	150 km	50 km	100 km
Detection Efficiency	68% (80%)	-	> 90%
Locating Accuracy	2-3 km	-	0.5 - 1.0 km
Time Accuracy	100 ms	100 ms	< 20 ms
Solution Algorithm	Closest Two Stns		All Stn Optimization

CSR

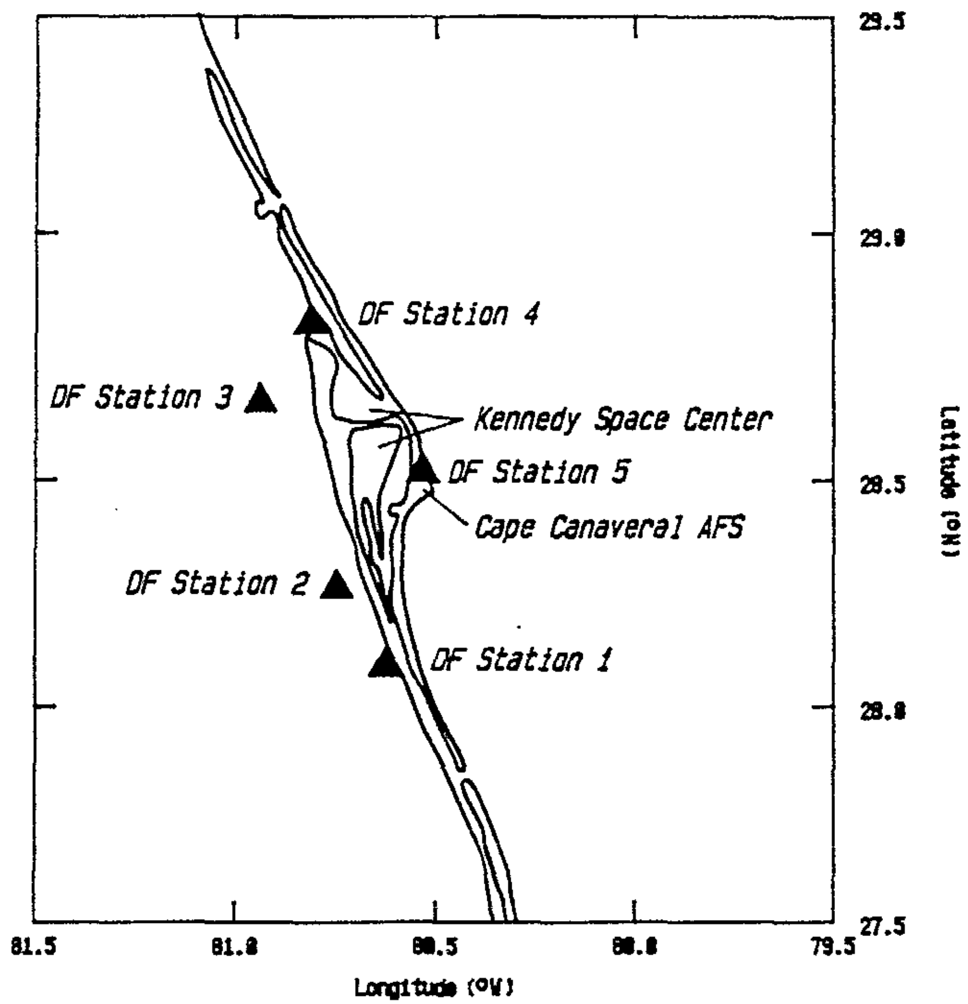
Present Network Configuration

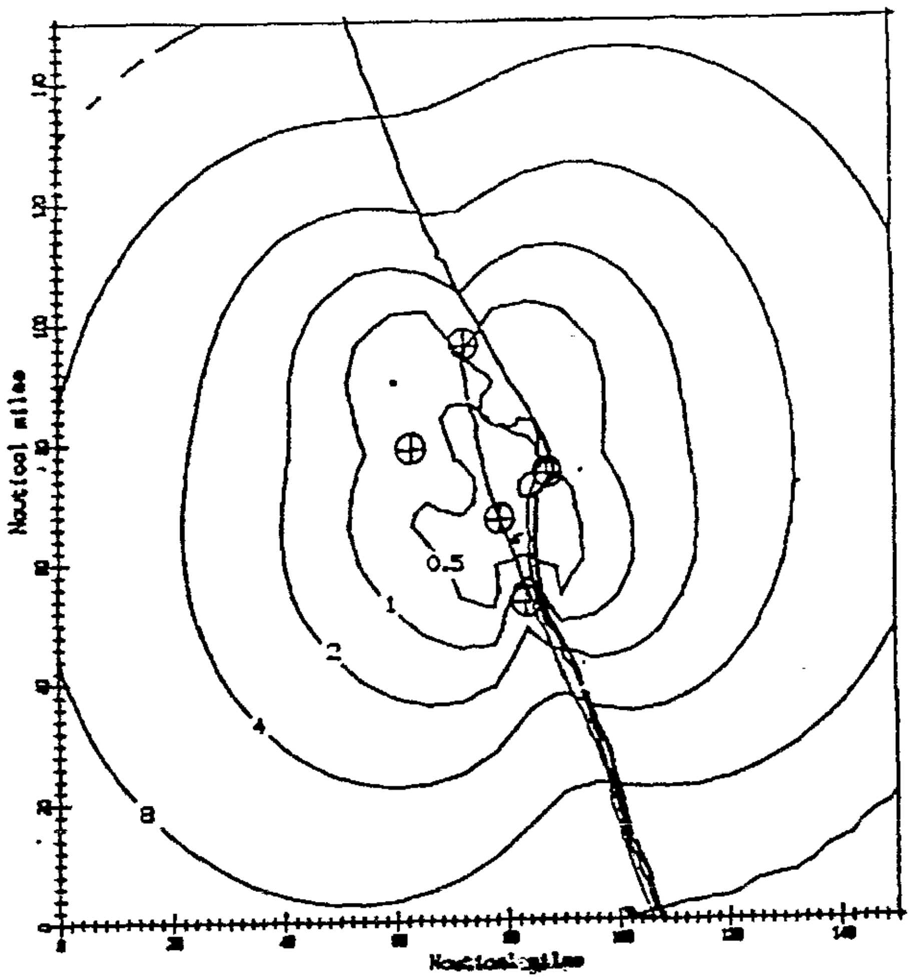


CSR


1
2
4
8
16
32

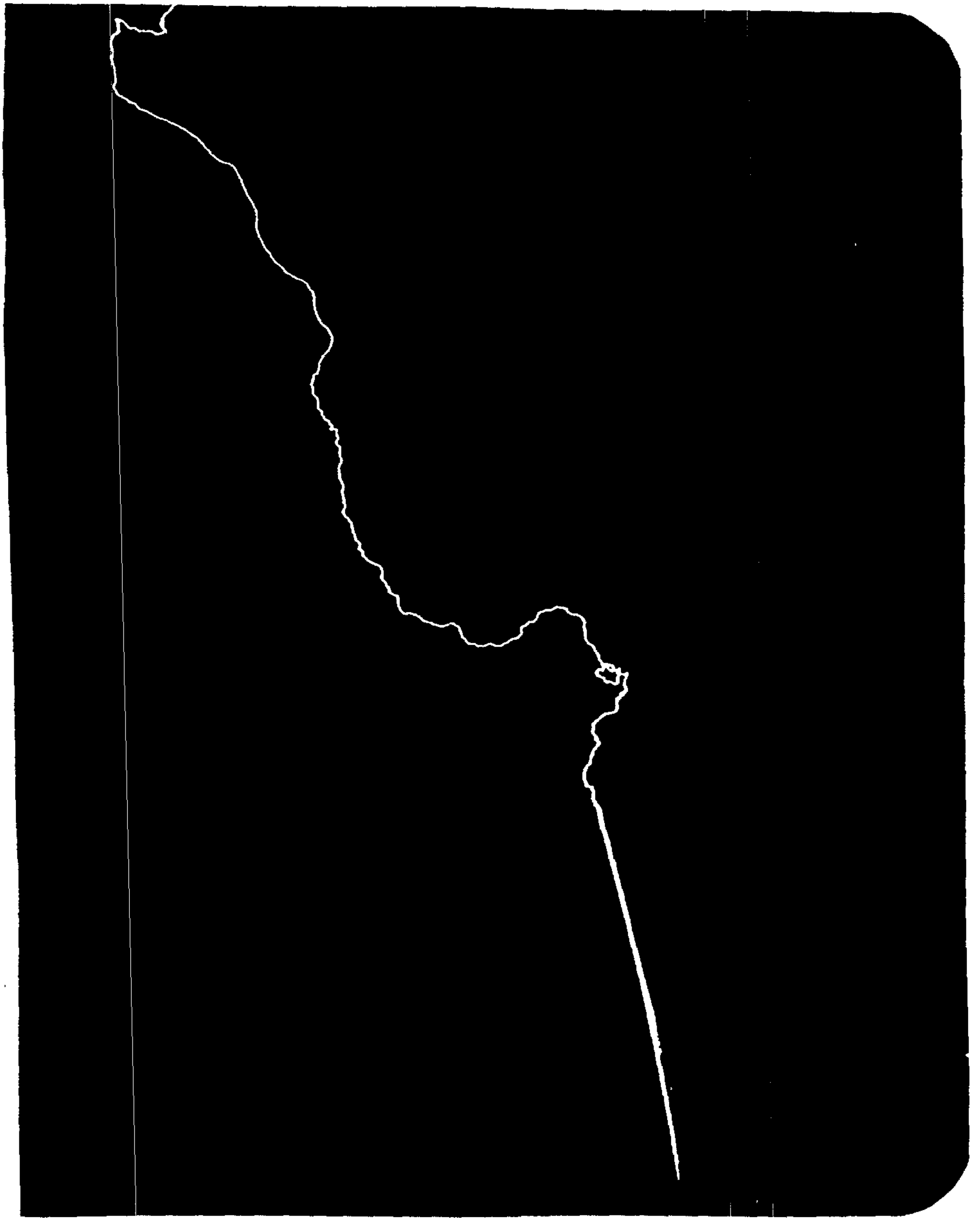
Planned Network Configuration

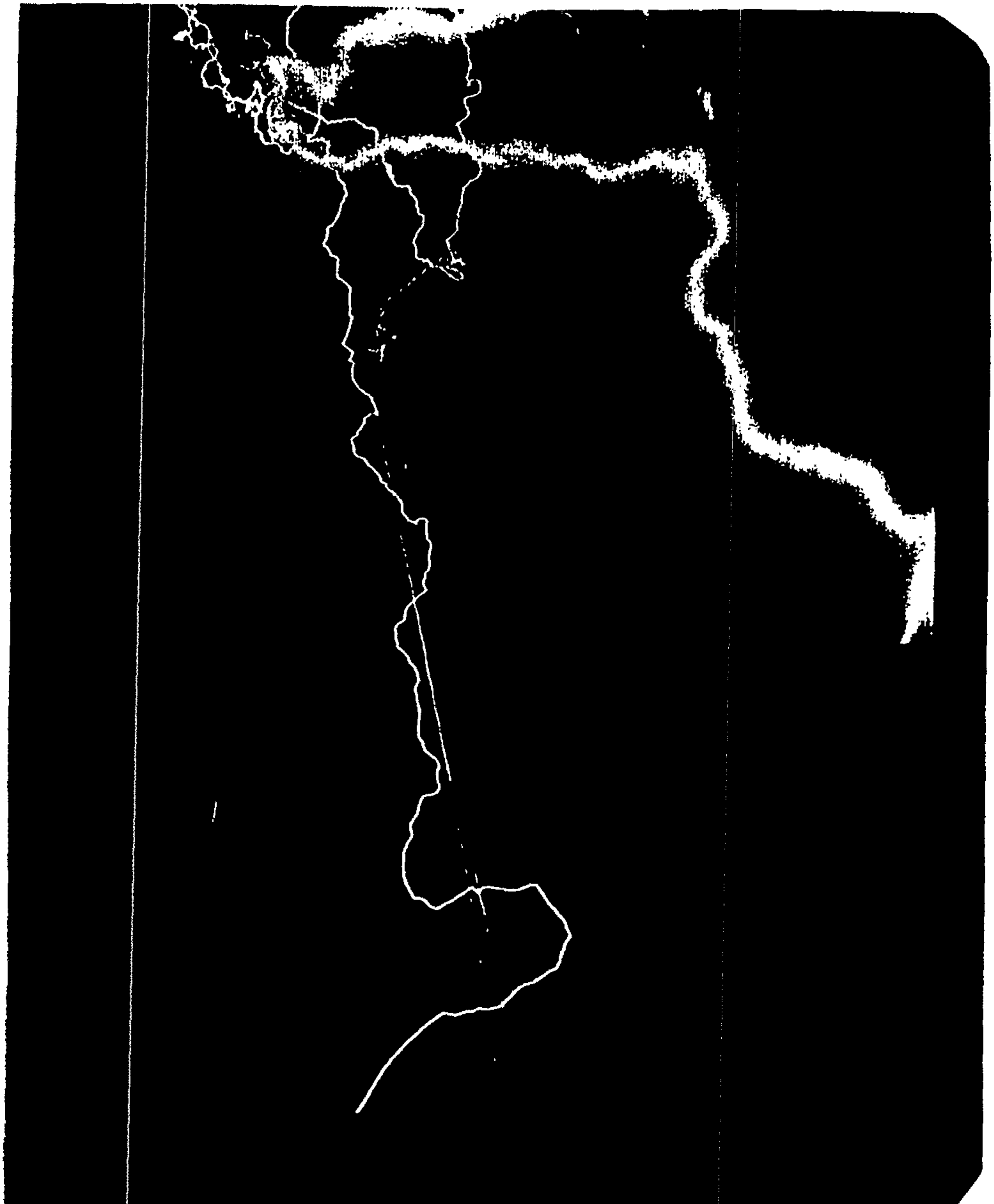



0.5
1
2
4
8
Nautical miles
Nautical miles
0
20
40
60
80
100
120
140

Related Support Initiatives

- Routine Ground-Truth Verification Program.
- Analysis of Peak Current Estimation Capability.
- Site-Error Calibration Procedures.
- Improved Antenna North Alignment Techniques.
- Techniques for Integrating SUNYA Data.

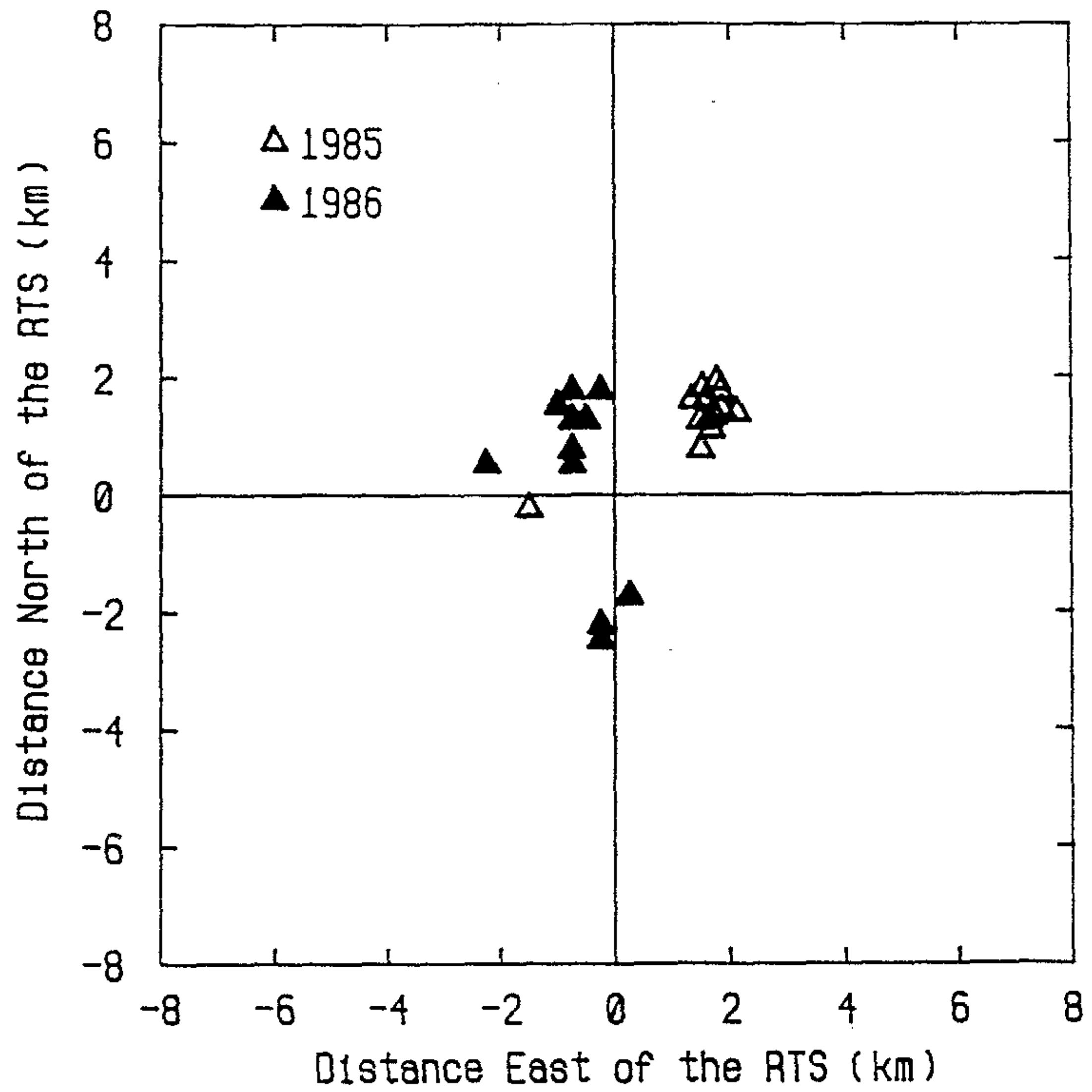


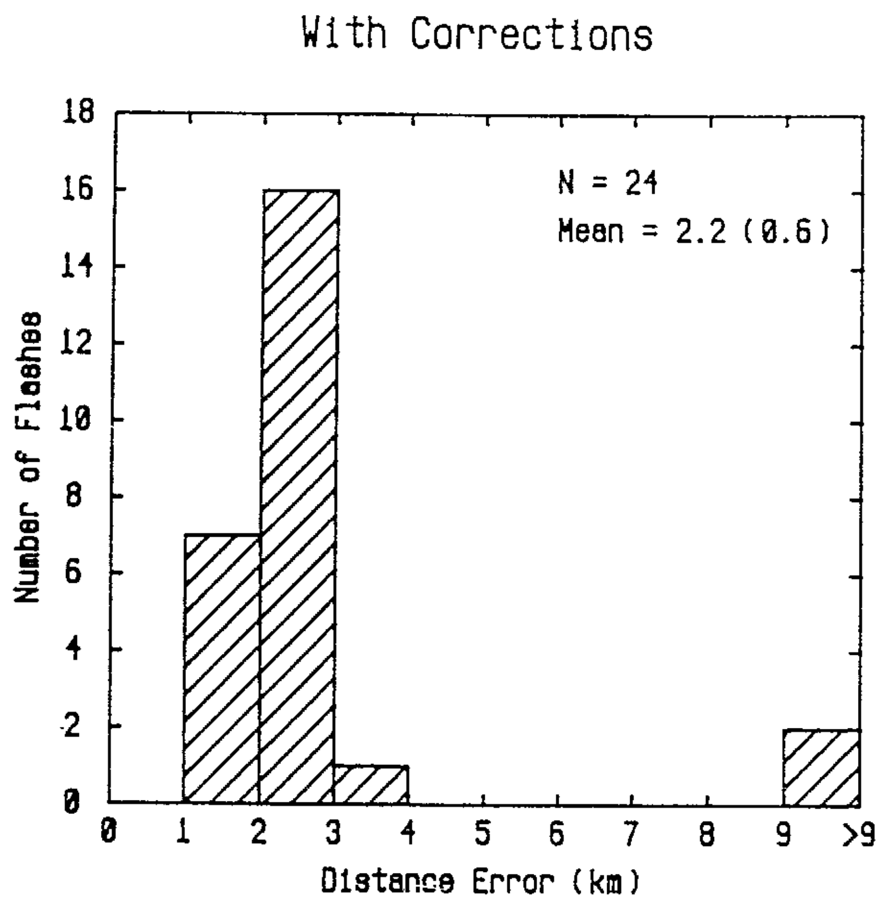


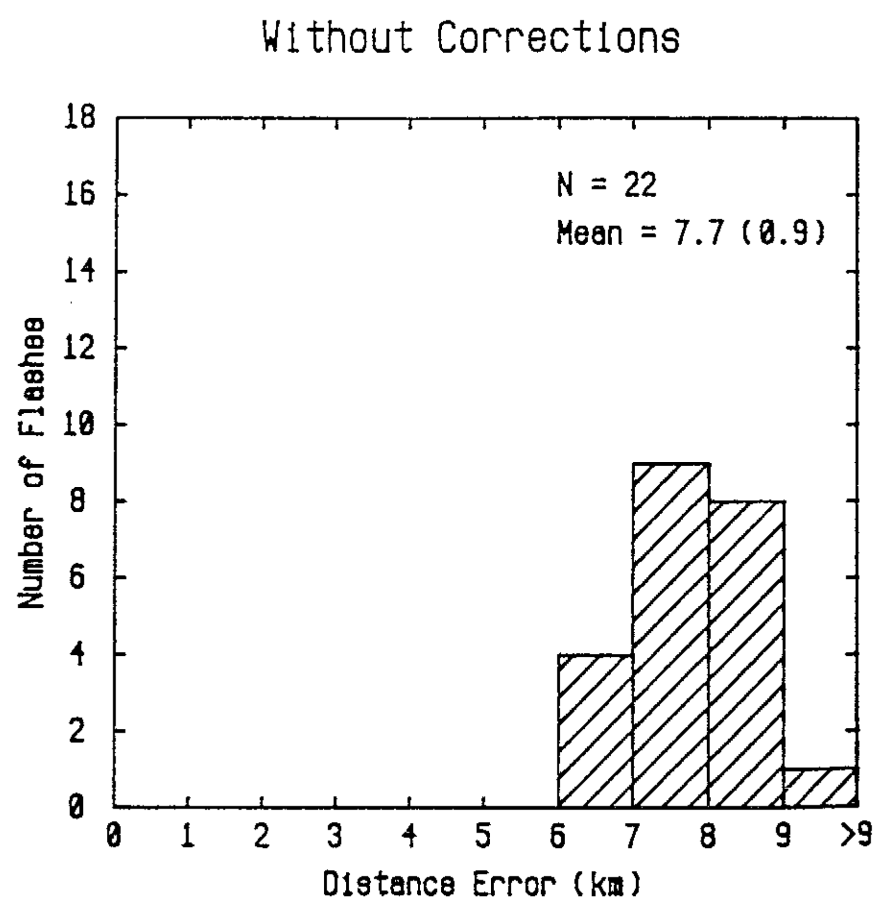
Event	ATS Time		LLP Time		Time Difference	Mean Deviation
8504	1909:51.100	5	1909:50.121	4	0.979	-0.079
8508	1948:39.750	3	1948:38.766	2	0.984	-0.074
8509	1953:52.053	12	1953:51.073	5	0.980	-0.078
8510	1959:40.092	5	1959:39.118	1	0.974	-0.084
8511	2005:02.757	7	2005:01.778	5	0.979	-0.079
8512	2009:58.530	4	2009:57.649	2	0.881	-0.177
8523	1945:37.030	2	1945:35.943	1	1.087	+0.029
8525	2009:51.820	1	2009:50.720	1	1.100	+0.042
8535	1446:50.175	12	1446:49.091	6	1.084	+0.026
8536	1536:57.892	9	1536:56.824	4	1.050	-0.008
8539	1819:51.685	3	1819:50.471	2	1.214	+0.156
8540	1821:56.941	6	1821:55.807	1	1.134	+0.076
8610	2035:15.784	4	2035:14.573	2	1.211	+0.153
8615	2056:40.922	8	2056:39.709	5	1.213	+0.155
8627	1728:22.062	3	1728:21.060	2	1.002	-0.056

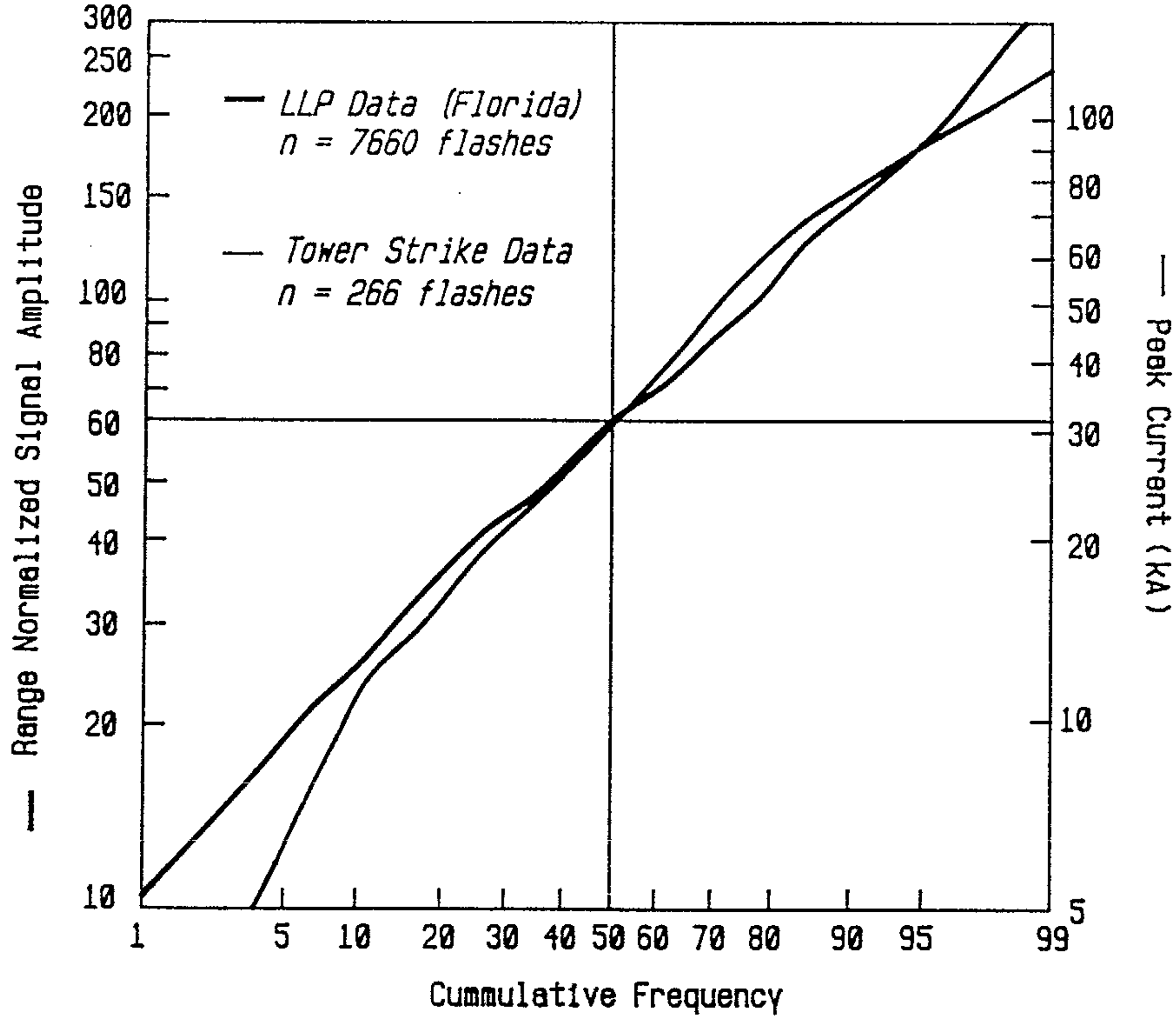
Mean Time Difference = 1.058 s
Standard Deviation = 0.102 s

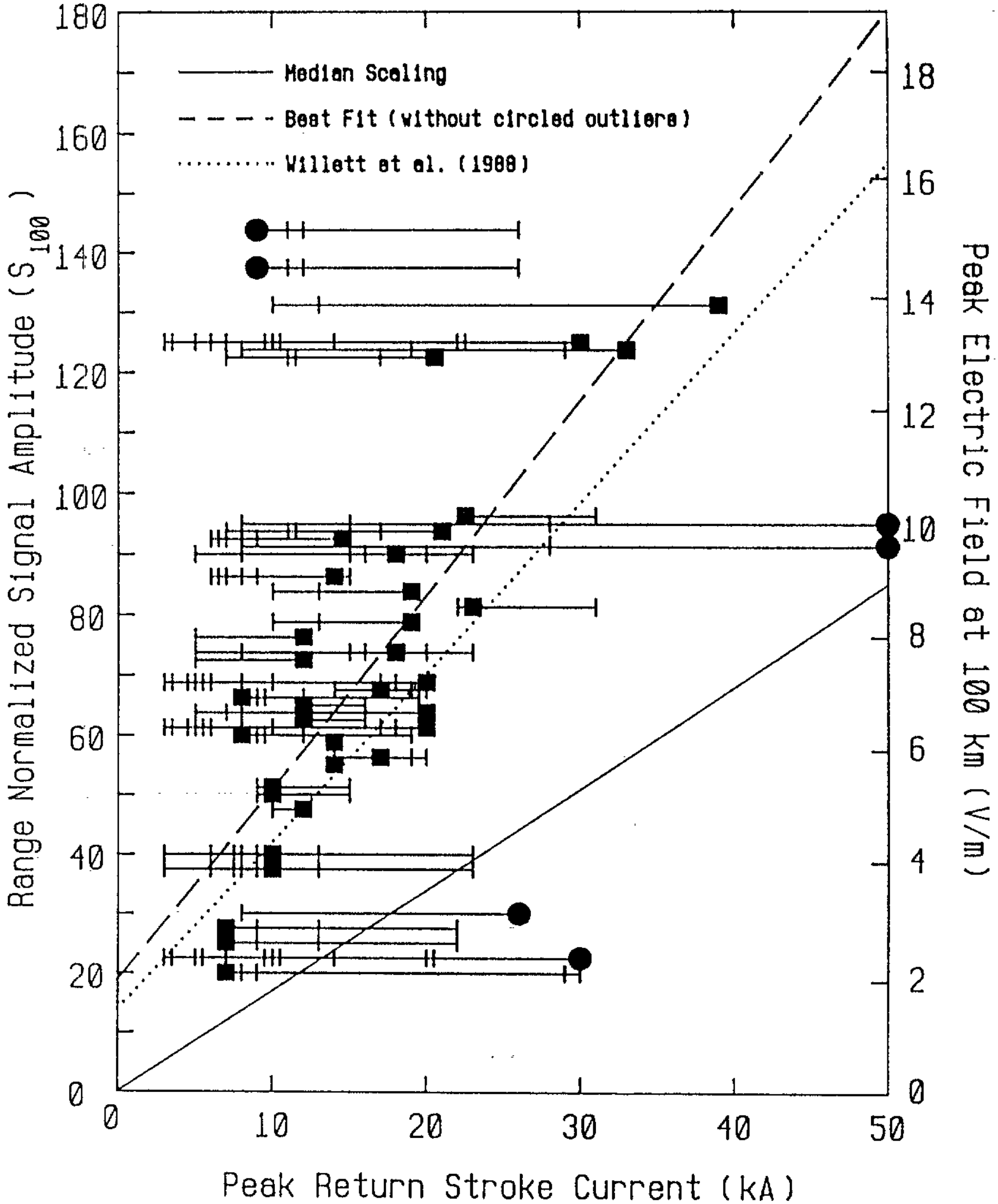
CSR


1985
1986
Distance North of the RTS (km)
Distance East of the RTS (km)
8
6
4
2
0
-2
-4
-6
-8
-8
-6
-4
-2
0
2
4
6
8


With Corrections
N = 24
Mean = 2.2 (0.6)
Number of Flashes
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4
5
6
7
8
9
>9
Distance Error (km)


Without Corrections
N = 22
Mean = 7.7 (0.9)
Number of Flashes
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4
5
6
7
8
9
>9
Distance Error (km)


LLP Data (Florida)
n = 7660 flashes
Tower Strike Data
n = 266 flashes
Range Normalized Signal Amplitude
300
250
200
150
100
80
60
50
40
30
20
10
Peak Current (kA)
100
80
60
50
40
30
20
10
5
1
5
10
20
30
40
50
60
70
80
90
95
99
Cummulative Frequency

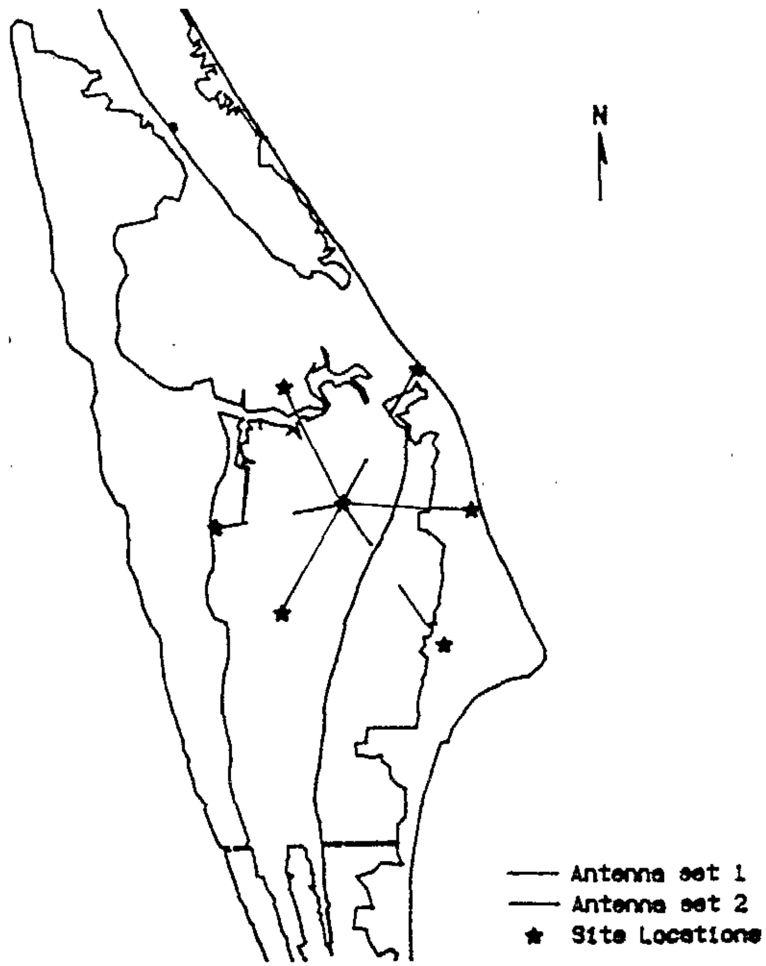


Median Scaling
Best Fit (without circled outliers)
Willett et al. (1988)
Range Normalized Signal Amplitude (S_{100})
Peak Electric Field at 100 km (V/m)
Peak Return Stroke Current (kA)
0
20
40
60
80
100
120
140
160
180
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50

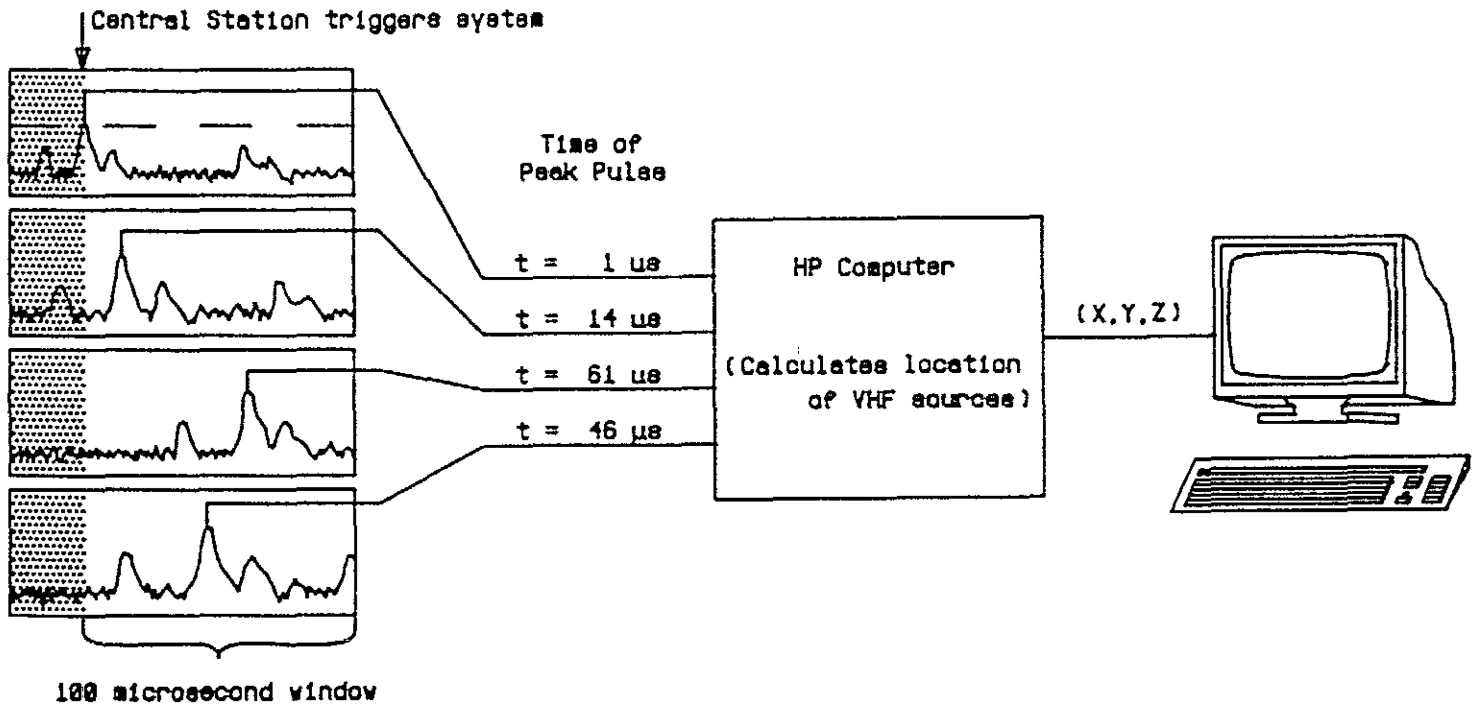
Lightning Detection and Ranging System (LDAR)

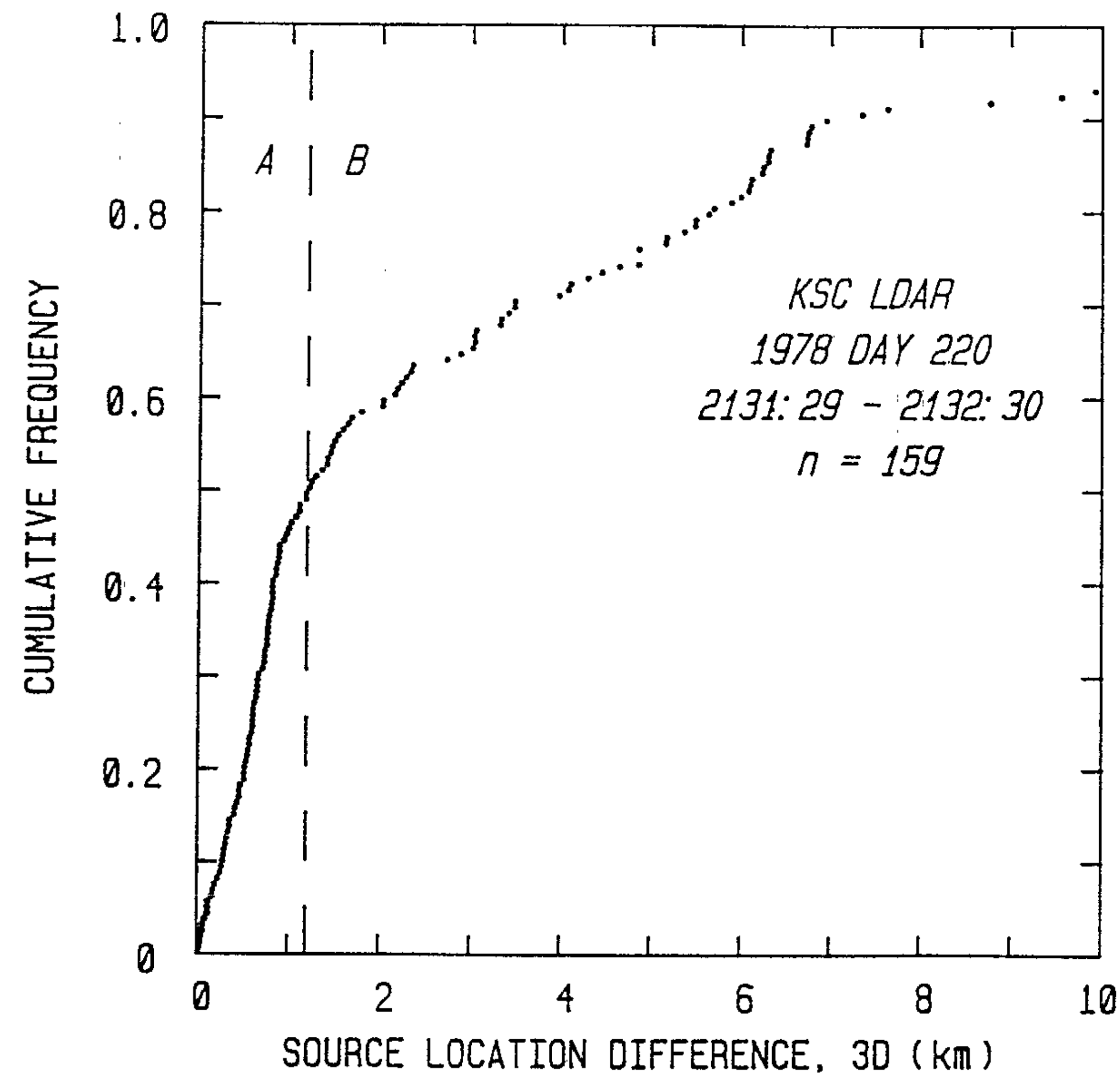
NASA TE-CID-3/INSTRUMENTATION AND MEASUREMENTS BRANCH

IN-CLOUD LIGHTNING DETECTION SYSTEM



TE-CID-3/INSTRUMENTATION AND MEASUREMENTS BRANCH




1.0
0.8
0.6
0.4
0.2
0
CUMULATIVE FREQUENCY
A
B
KSC LDAR
1978 DAY 220
2131:29 - 2132:30
n = 159
0
2
4
6
8
10
SOURCE LOCATION DIFFERENCE, 3D (km)

Airborne Field Mill Program
(ABFM)

AIRBORNE FIELD MILL PROGRAM (ABFM)

- Joint NASA-Air Force program.
- Objective is to improve launch availability.
  - Refine launch minima through improved understanding of threat environment.
  - Develop a DOL capability if proven necessary.
- Successful flight operations conducted on summer clouds.
  - NMIMT SPTVAR (1988 and 1989).
  - SRI/Aeroment Lear (1989).
- Full year investigation about to get underway.
  - NASA Langley Lear.
  - NASA Marshall field mills.
  - NASA KSC/ESMC operations support.

CSR

ABSTRACT

Lightning and Thunderstorm Research at Wallops Flight Facility

The NASA Goddard\ Wallops Flight Facility is located on the Atlantic coast of the Eastern Shore of Virginia. Our interested in thunderstorms began in the early 1980's with the NASA Storm Hazards Program. That program was initiated to learn the nature of the hazard posed to aircraft by severe thunderstorms, especially from direct lightning strikes. A F106 Delta jet airplane was directed into active thunderstorms to measure the effects of direct lightning strikes. The Wallops role was to locate and vector the aircraft into storm cells where a lightning strike would be likely but where there would be no hail. To satisfy this role we acquired and used a diverse array of instrumentation which became a part of the Atmospheric Sciences Research Facility (ASRF). Figure 1 is graphical representation of that instrumentation.

The two research radars shown in figure 2 were the primary tools used to locate and select candidate storm cells. The UHF band radar in the foreground could detect the ionized lightning channels within the cell and the SPANDAR s-band radar could display the precipitation structure of the storm and highlight areas of possible hail. The c-band radars tracked the aircraft and the National Weather Service radar at Patuxent provided early warning of approaching storms. The Lightning Location and Protection (LLP) system, which has since been integrated into the National Lightning Data Network (NLDN), detected cloud-to-ground lightning activity over a large area while the Lightning Direction and Ranging (LDAR) system detected all types of lightning activity within 60 miles of Wallops. Likewise the spherics system which recorded the spherics signal at several discrete frequencies covered a large area while the electric field sensors only recorded electric field changes in the local area. Figure 3. shows the VHF radiation detected by the LDAR system and the resulting electric field changes from a single three stroke lightning flash.

With this array of instrumentation, we were able to successfully vector the F106 so that it was struck over 700 times. The capabilities we developed have supported a large number of other experiments at Wallops in recent years. The Thunderstorm Rocket Series was a group of experiments investigating the coupling of thunderstorms with the ionosphere including the generation of whistlers and trimpes. The Storm Dynamics program exploited the unique capabilities of the two research radars to map lightning activity within thunderstorms. Figure 4. is a sketch of how

the UHF radar was used to detect ionized channels. Figure 5. is a sample of the raw UHF data and figure 6. is a composite of the reflectivity and lightning activity.

The facilities of the ASRF are available to interested researchers. Requests should be directed to Mr. Joe McGoogan, Director of SPOD, NASA Wallops Flight Facility, Wallops Island, VA 23337. Call Dr. John Gerlach 804-824-1188 for additional information.

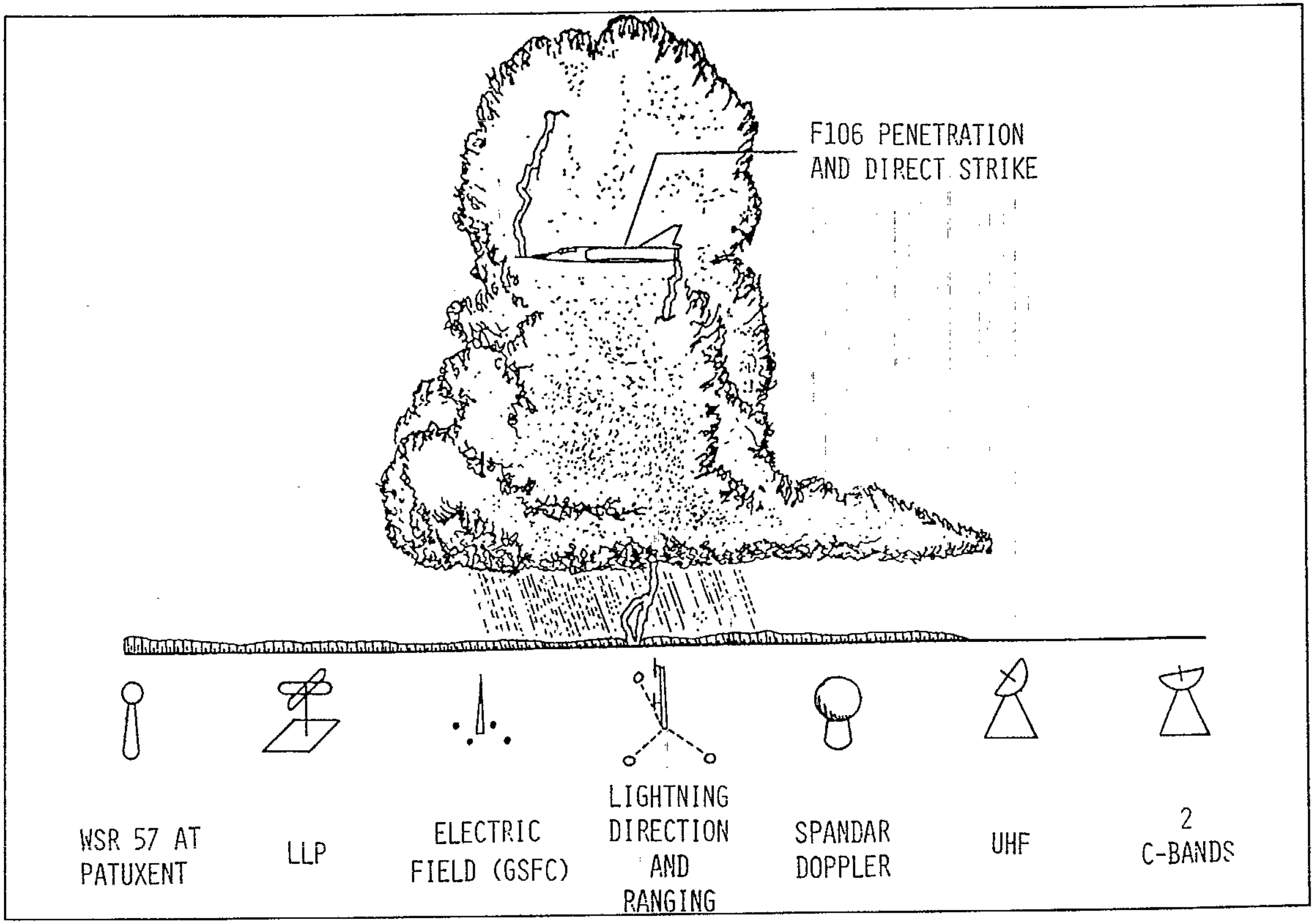


Figure 1. Storm hazards operations and WFF instrumentation used to support it.

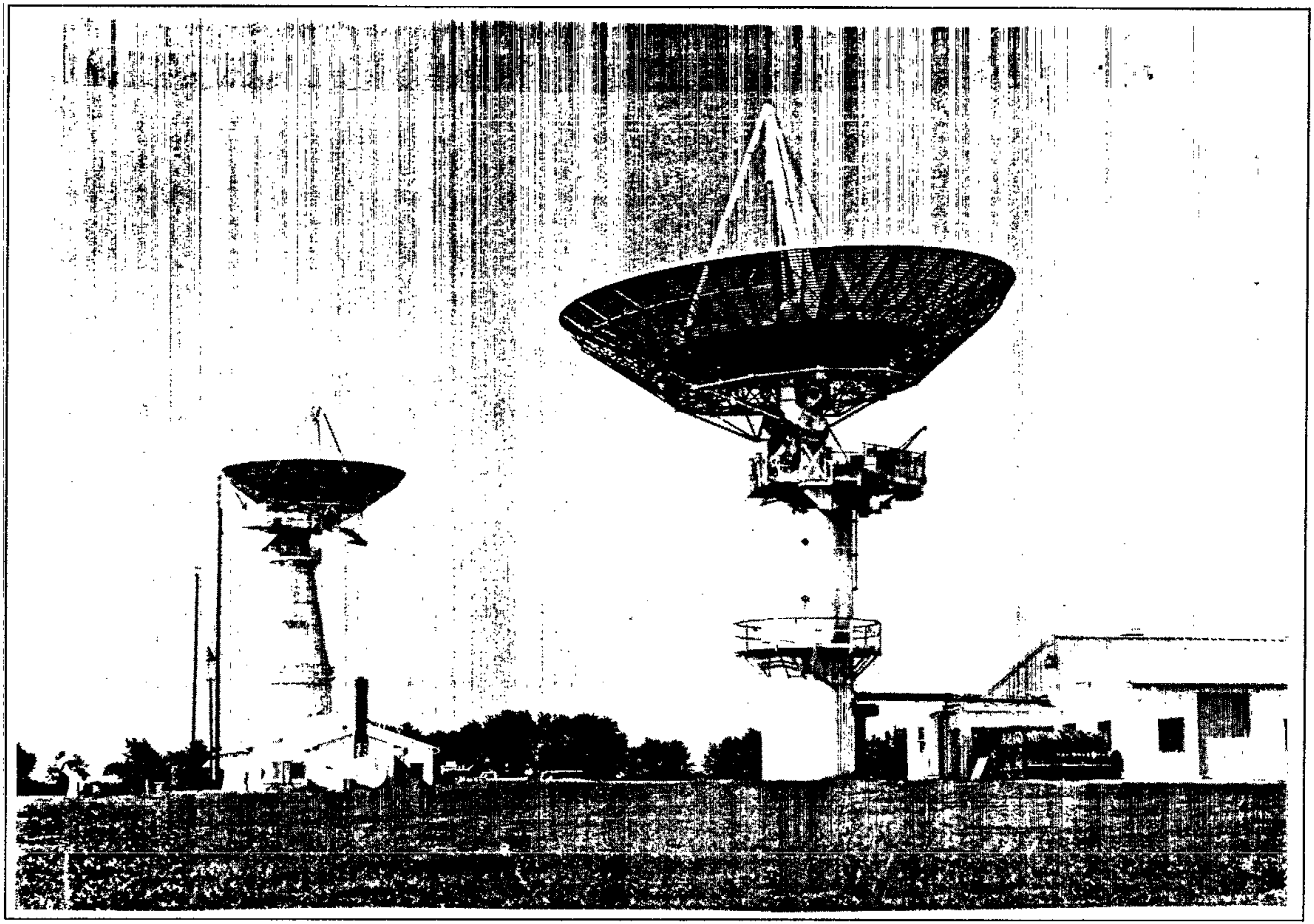


Figure 2. Research radars at WFF. UHF in the foreground and SPANDAR in the background.

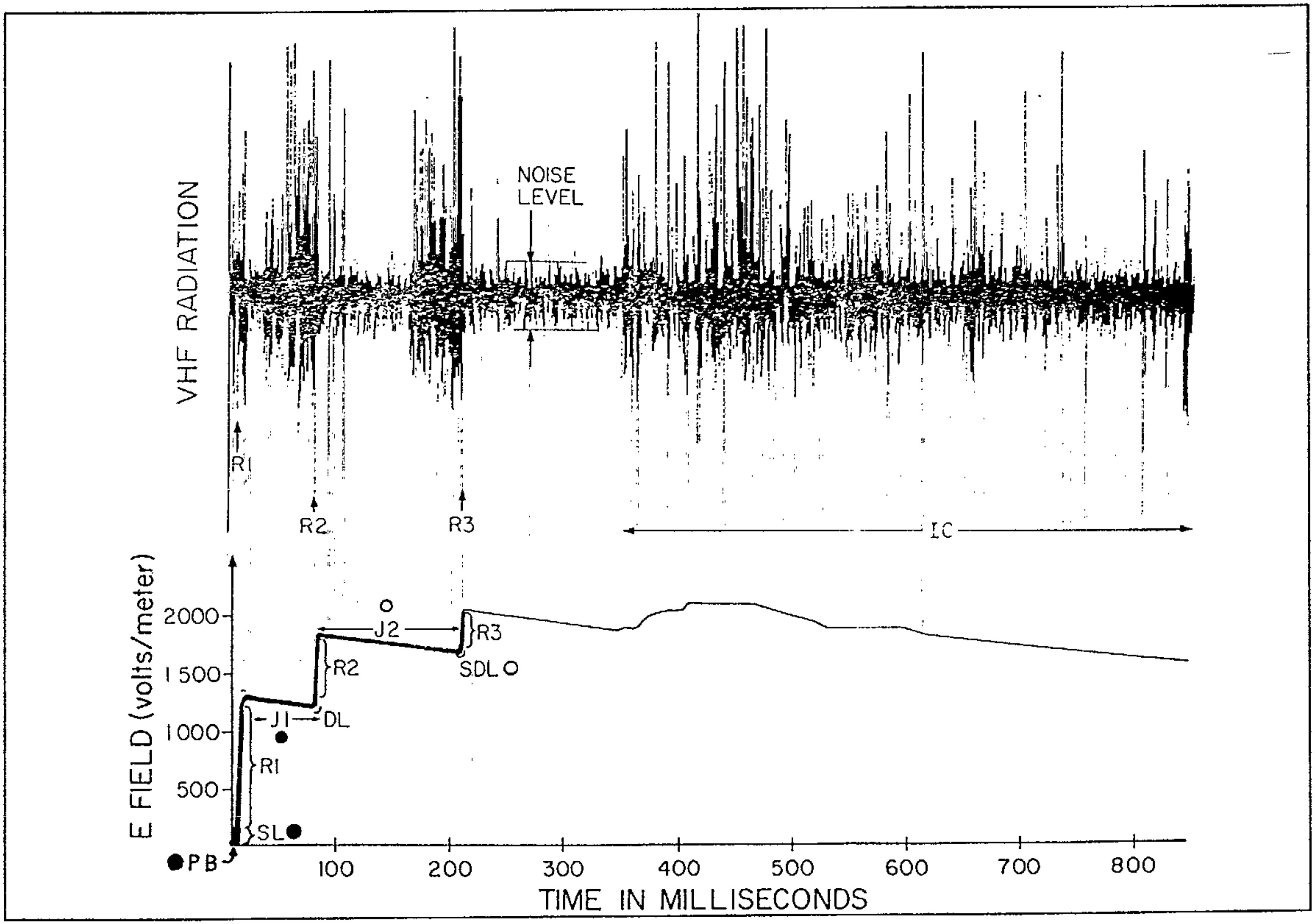


Figure 3. Radiation and electric field changes from a single lightning flash.

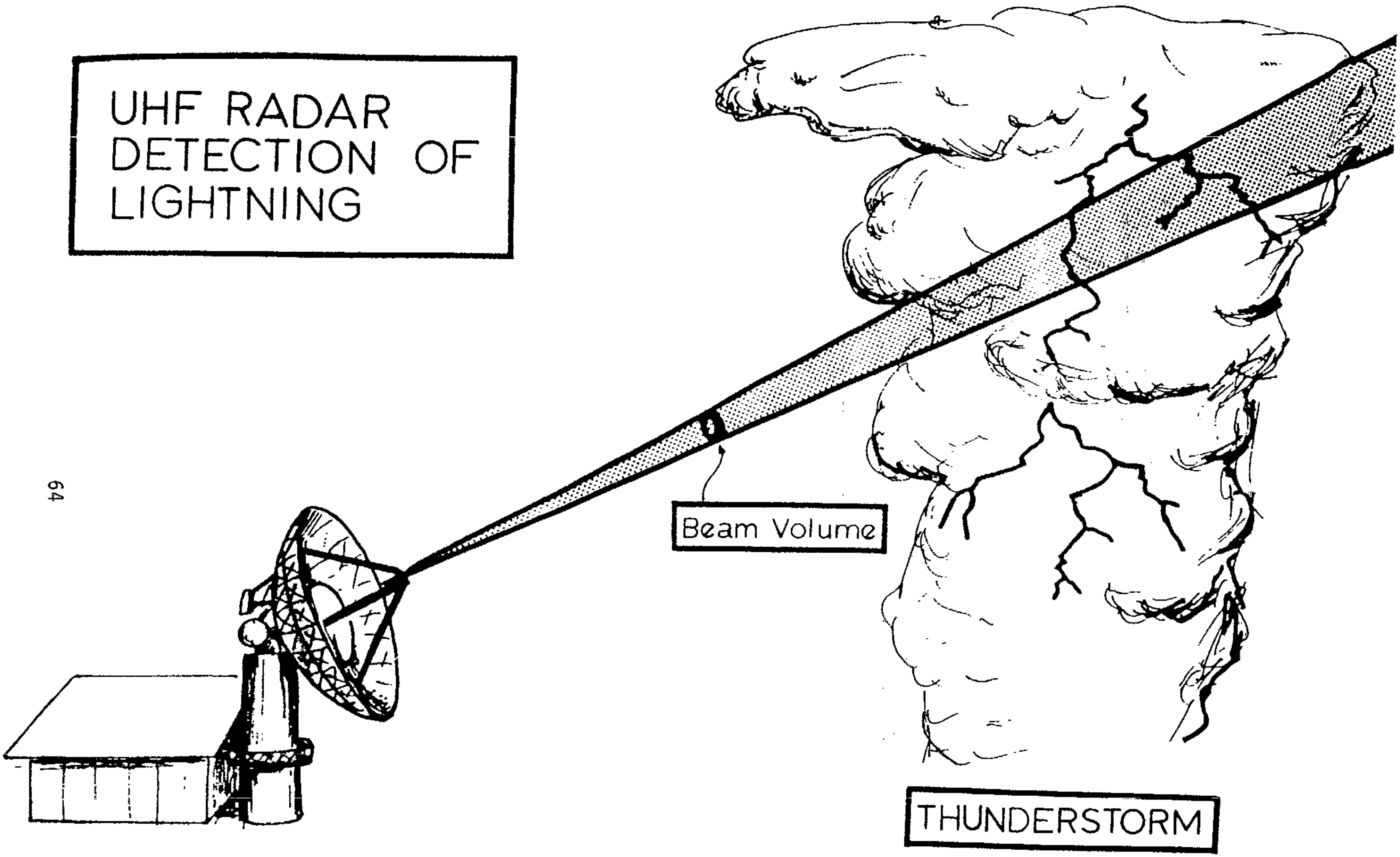


Figure 4. UHF radar detection of lightning.

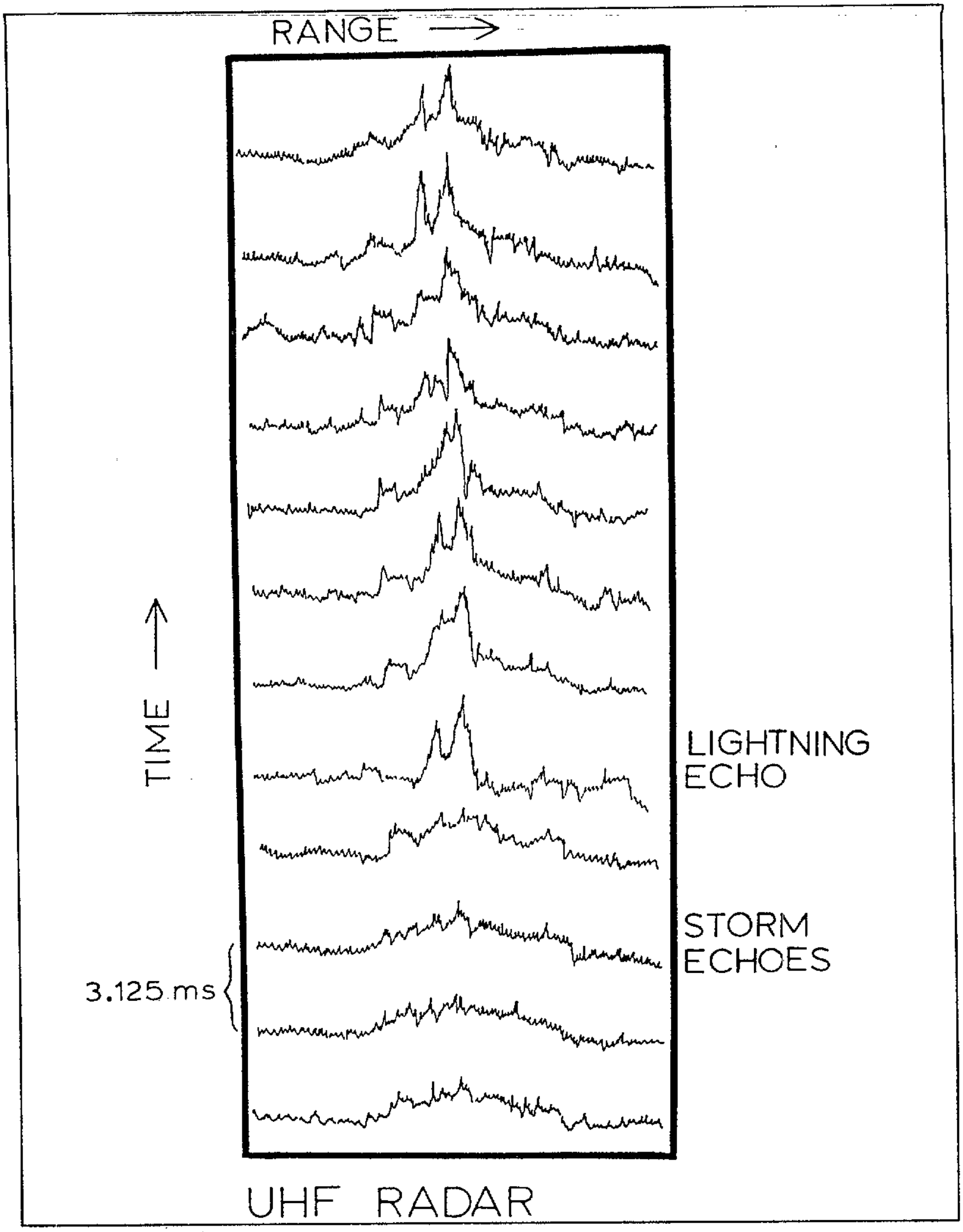


Figure 5. Raw UHF data showing returns from storm cells and lightning.

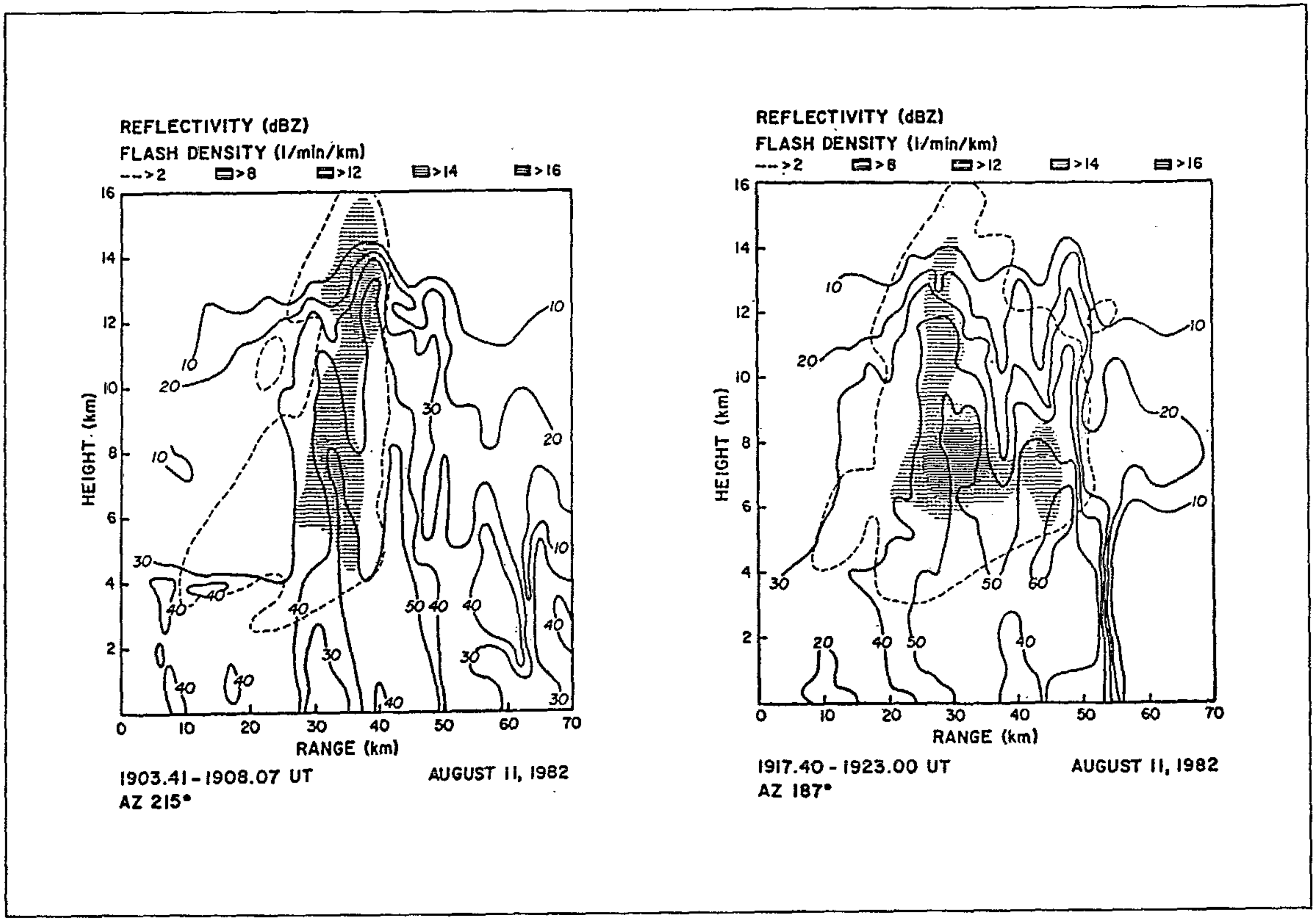


Figure 6. Composite of lightning and reflectivity data. (from Geophy. Res. Lett., 11, 1, pp 61-64)

LIGHTNING-RELATED CURRENTS IN CONDUCTORS

Leslie C. Hale
Communications and Space Sciences Laboratory
Penn State University
University Park, PA 16802

What the author is asking you to consider is the possibility that much of the electrical energy associated with lightning has been overlooked in most published work on the subject. It is certainly true that the most severe threat is the direct strike, and that the energy associated with this and the resulting fields provide the fast waveforms which can result in the disruption of electronics. However, we have observed an additional component, both underground and in the ionosphere, which generally deposits much more energy external to the lightning channel than that due to electromagnetic radiation. This component is due to charge which was not directly involved in the stroke itself, including the injected Wilson "monopoles" and other atmospheric space charge, and is akin to capacitive discharge. Kasemir [1971] used a single capacitor in an electrical representation of a thundercloud and Berger [1977] used cloud-to-ground capacitance to explain coupling involved in underground blasting accidents. In order to explain unexpectedly long duration electric field transients observed above a thunderstorm (by both Penn State and Cornell groups), Hale [1983] invoked a model similar to that shown in Figure 1, involving both capacitive effects. An important point is that the lowest resistance from the cloud top back to earth is via the ionosphere, which is a "grounded" conductor. (At DC, the ionosphere-to-earth resistance is a few hundred ohms, at ULF it is a few farads capacitance, and at higher frequencies a complex transmission line impedance which is still very low compared to the thundercloud impedances.) The meteorological current generator charges the cloud capacitor directly and, via the ionosphere and global circuit, the cloud-to-ground capacitance. It is then a race to see which discharges, but since both cloud-to-ground (CG) and intracloud (IC) discharges do occur we can assume the stored energy is comparable in the two capacitors. This is borne out by the fact that the observed IC and CG waveforms tend to be similar in shape and amplitude, but reversed in polarity.

The key point is that when one of the CG and IC capacitors discharges, the other one dumps most of its stored energy into the ionosphere and global circuit and to recharging the discharged capacitor. Since Krider and Guo [1983] have shown that the energy radiated from the stroke is less than 1% of the associated stroke energy, it is seen that the capacitance discharge mechanism can deposit a much larger energy into the relevant conducting regions external to the cloud than electromagnetic radiation. The associated currents will tend to "focus" in conductors such pipelines, underground facilities, rocket launch rails, etc.

While the "capacitor" model gives an idea of where the additional energy comes from, it does not accurately predict the observed waveforms. It can be improved by additional lumped elements. This can and has been extended to a Cartesian grid of resistors and capacitors, both using a computer model [e.g. Nisbet, 1983] and a hardware model (John Willett, private communication). However, it is difficult to simulate inductive effects in such models and the rise time of the pulse generator used by Willett does not come near to scaling to values realistic for lightning. Some computer models have obtained wrong answers by "forcing" the conservative field, Curl E = O condition.

Most of our intervening work in this area has concentrated on solving the field problem to obtain the currents and fields. The method used is the injection of a C.T.R. Wilson monopole at an appropriate height by an appropriate current waveform and then solving for the response (See Figure 2a). There is a history of such calculations that will be reviewed briefly. The Wilson model [1920] successfully predicted "field changes," and for many years the unexpectedly fast recovery was attributed to processes inside the thundercloud. Perhaps the first quantitative statement of how the atmosphere outside of the cloud was involved in the response was by Tamura [1954], who used the conservative (Curl E = O) solution is terms of the relaxation time (ε/σ) at the point of observation. Although this was a step forward at the time, the subsequent use of the conservative field solution has obscured the energy associated with the capacitance discharge mechanism, which is forbidden by Curl E = O. Other ways of throwing out the correct solution involve the use of images, the assumption of the radiation, induction, and electrostatic trichotomy (these terms only have distinct meaning in special cases), and statements about the Maxwell current density being "slowly varying" between lightning strokes (although this statement is all right if the word density is omitted, it then being a statement of Stokes' theorem).

In subsequent papers in the Quart. J. Roy. Met. Soc. [1971 and 1972], A.J. Illingworth loudly and clearly reiterated the importance of atmospheric conductivity, particularly of the higher conductivity upper regions. This type of calculation was extended by Dejnakarintra and Park [1974], Greifinger and Greifinger [1976], and Holtzworth and Chiu [1982]. Of particular interest is the formulation of Carl and Phyllis Greifinger. They introduced the idea of a "moving capacitor plate" (see Figure 2b) which starts in the high ionosphere in response to a lightning stroke and moves downward, with the altitude determined as where time after the stroke is equal to the local relaxation time. The "plate" plays the role of determining the boundary between conduction and displacement current. Combining this picture with the simple fact that the ionosphere is "grounded" (or "earthed" in England) through the global circuit gives rise to Equation 1 (which is general) and Equation 2 (for the special case of an exponential conductivity profile). This shows that, contrary to most writing on the subject, a huge pulse of current flows to the ionosphere and returns in the earth subsequent to a lightning stroke.

Because of the approximate nature of this calculation, we did not attempt to publish it immediately. M.E. Baginski developed a large finite element computer program to model the problem. When, on the first try, this agreed almost precisely with the analytical solutions for the total current in the expected range of validity (milliseconds to seconds), the comparison (see Figure 3) was submitted for publication, and appeared in Nature after many months of sparring with reviewers [Hale and Baginski, 1987].

Subsequently we were able to experimentally verify (see Figure 4) the predicted long "recovery" pulse with electric field measurements made above a thundercloud, with lightning located by the SUNY-Albany network (R.E. Orville, private communication). This is compared with monopoles injected at 6 and 8 km altitude, computed using the conductivity profile measured by the rocket-launched, parachute-borne payload that also observed the electric field.

The main point of the paper is that this large pulse of currents to the ionosphere must return in the earth below the storm, because of the low impedance of the global circuit, as well as cloud-top to ground capacitive coupling. We find that there is a dearth of information on transients in earthed or underground locations with sufficient diagnostics to describe the physical situation.

Figures 5 and 6 show some of our own data relevant to this problem. The sponsor of this measurement requested that we only discuss this data in a generic sense. Suffice it to say that at distances of tens of kilometers from located lightning, the transient currents in an underground facility were much larger than predicted by LEMP codes. This may be due to the processes described above, with the currents "focussing" in the buried conducting facility.

Although it cannot be easily proven, the author believes that charge-coupling processes similar to those described in this paper may also alter the EMP scenario. He was at Los Alamos from 1957 to 1962 during and just before the last atmospheric nuclear weapons tests. Many bizarre effects were described in unclassified sources which cannot be readily explained by unclassified EMP scenarios which are generally accepted. The author believes that if we do not yet generally agree on what happens in lightning phenomena which are readily available for observation then it is unlikely that we understand relatively unobserved phenomena such as EMP.

REFERENCES

Berger, K., "Protection of underground blasting operations," in: Golde, R.H. (ed), Lightning, Vol 2, Academic Press (1977)

Dejnakarintra, M. and C.G. Park, J. Geophys. Res. 79, 1903, 1974

Greifinger, C. amd P. Greifinger, J. Geophys. Res., 81, 2237, 1976

Hale, L.C., "Experimentally determined factors influencing electrical coupling mechanisms," Weather and Climate Responses to Solar Variations, in B.M. McCormac (ed), Colorado Associated University Press, Boulder (1983), p. 309

Hale, L.C., and M.E. Baginski, "Current to the ionosphere following a lightning stroke," Nature, 329, 814, 1987.

Holzworth, R.H. and Y.T. Chiu in: Handbook of Atmospherics, Vol II, p.1, CRC Press, New York 1982.

Illingworth, A.J., Quart. J. Roy. Met. Soc., 98, 604, 1972.

Kasemir, H.W., Pure Appl. Geophys. 84, 64, 1971.

Krider, E.P. and C. Guo, "The peak electromagnetic power radiated by lightning return strokes," J. Geophys. Res., 88, 8471, 1983.

Nisbet, J.S., J. Atmos. Sci., 40, 2855, 1983.

Wilson, C.T.R., Phil. Trans. A. 221, 73, 1920.

APPENDIX A

Equations [1] and [2] giving waveform of current pulse in earth and ionosphere following lightning stroke. This is paradigmatic "impulse response".

Although yielding an understanding of the source of additional energy implied by the measurements, the model of Figure 1 does not accurately predict the waveform of current to the ionosphere in the presence of a realistic atmosphere whose conductivity varies continuously by many orders of magnitude between the earth and ionosphere. This waveform can be estimated using a physical viewpoint adapted from C. and P. Greifinger [1976] and shown in Figure 2.

Cloud-to-earth lightning is described by the injection of a "C.T.R. Wilson monopole" of charge Q_o at an appropriate height h_m at $t = 0$. Initially, the electrostatic solution obtains between the earth and ionosphere (the validity of this is restricted to times greater than $\sim 10^{-3}$ sec., because of speed-of-light effects). A subsequent transient, governed by the complete Maxwell's equations, then ensues. This transient proceeds most rapidly in the ionosphere, with the role of the local relaxation time τ_r being to define the boundary (at an altitude h_i) between conduction and displacement current dominated regions moving downward from the ionosphere according to $t = \tau_r$. Using the approximations that this diffuse boundary is sharp and that a sequence of quasi-static solutions gives a valid expression for the total current to the ionosphere, I_m, the following relation is derived:

$$I_m = \frac{fQ}{I_m} + \frac{d(fQ)}{dt} \quad \text{where: } f = h_m/h_i \qquad [1]$$

For a conductivity profile increasing exponentially with altitude, frequently used to approximate the atmospheric conductivity, this reduces to:

$$I_m = \frac{Q_o\, h_m}{h_\sigma} \frac{\varepsilon^{-t/\tau_m}}{t(\ln \tau_o/t)^2} \qquad [2]$$

where: τ_m is the relaxation time at h_m. h_σ is the conductivity scale height. τ_o is the air relaxation time at the surface. This expression is only valid for $t \ll \tau_m$.

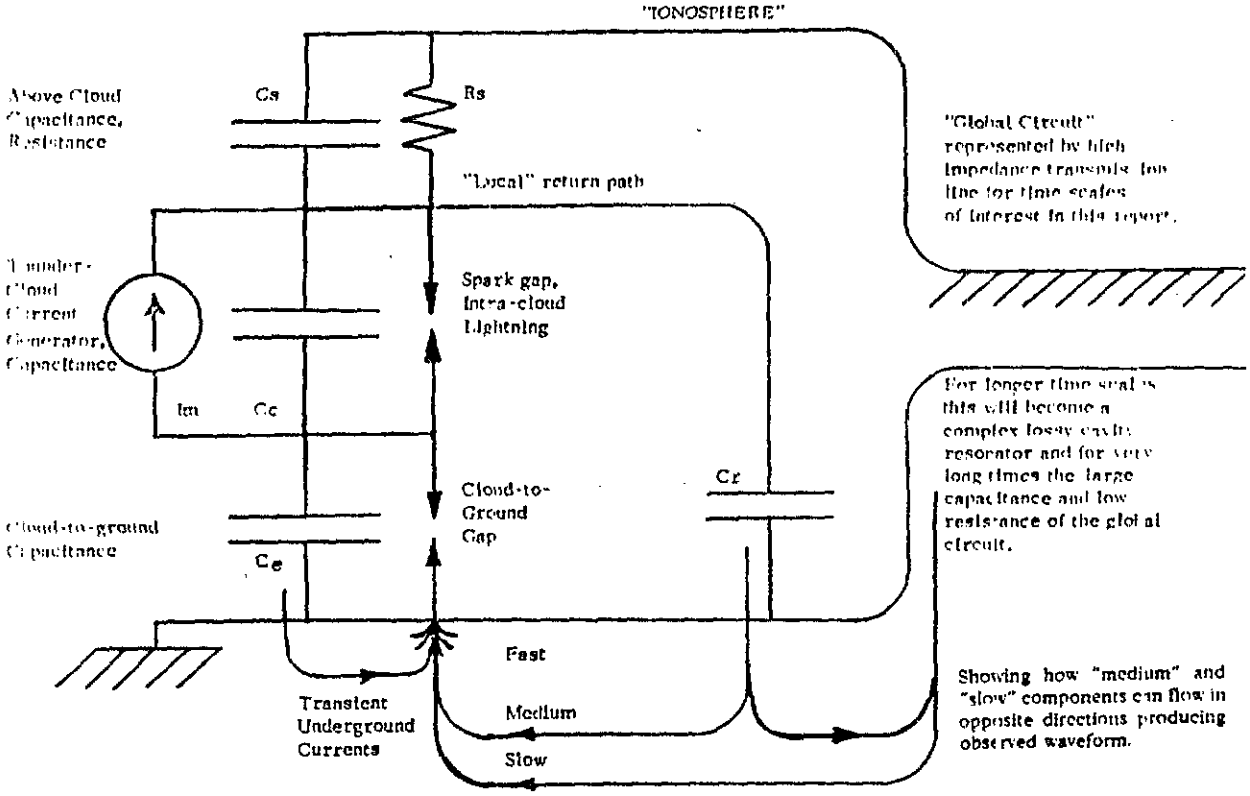


Figure 1. Approximate model showing basic processes necessary to explain observed currents in ionosphere and earth.

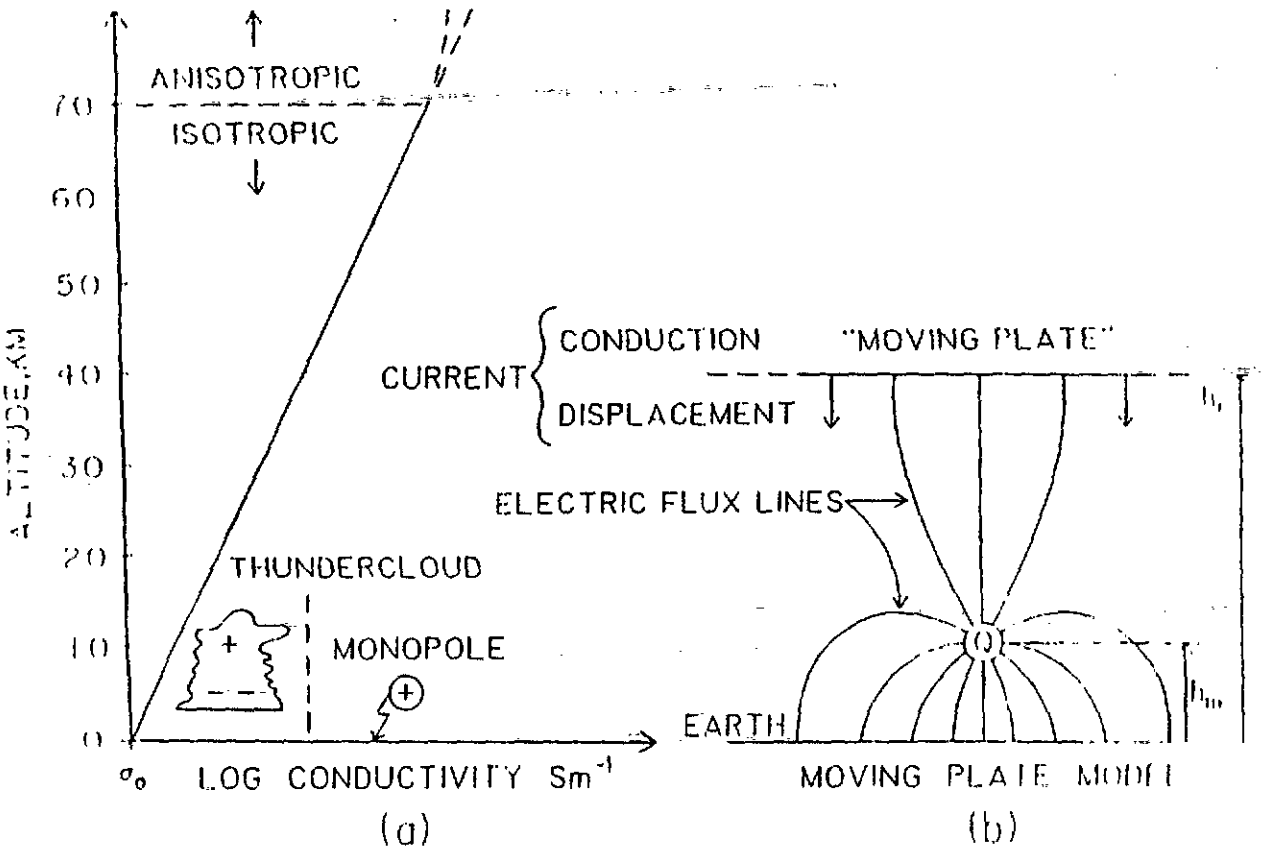


Figure 2. (a) Showing how C.T.R. Wilson "monopole" is inserted at the altitude of neutralized charge by lightning currents. (b) Showing "moving plate" model to explain transient currents generated by monopole Q.

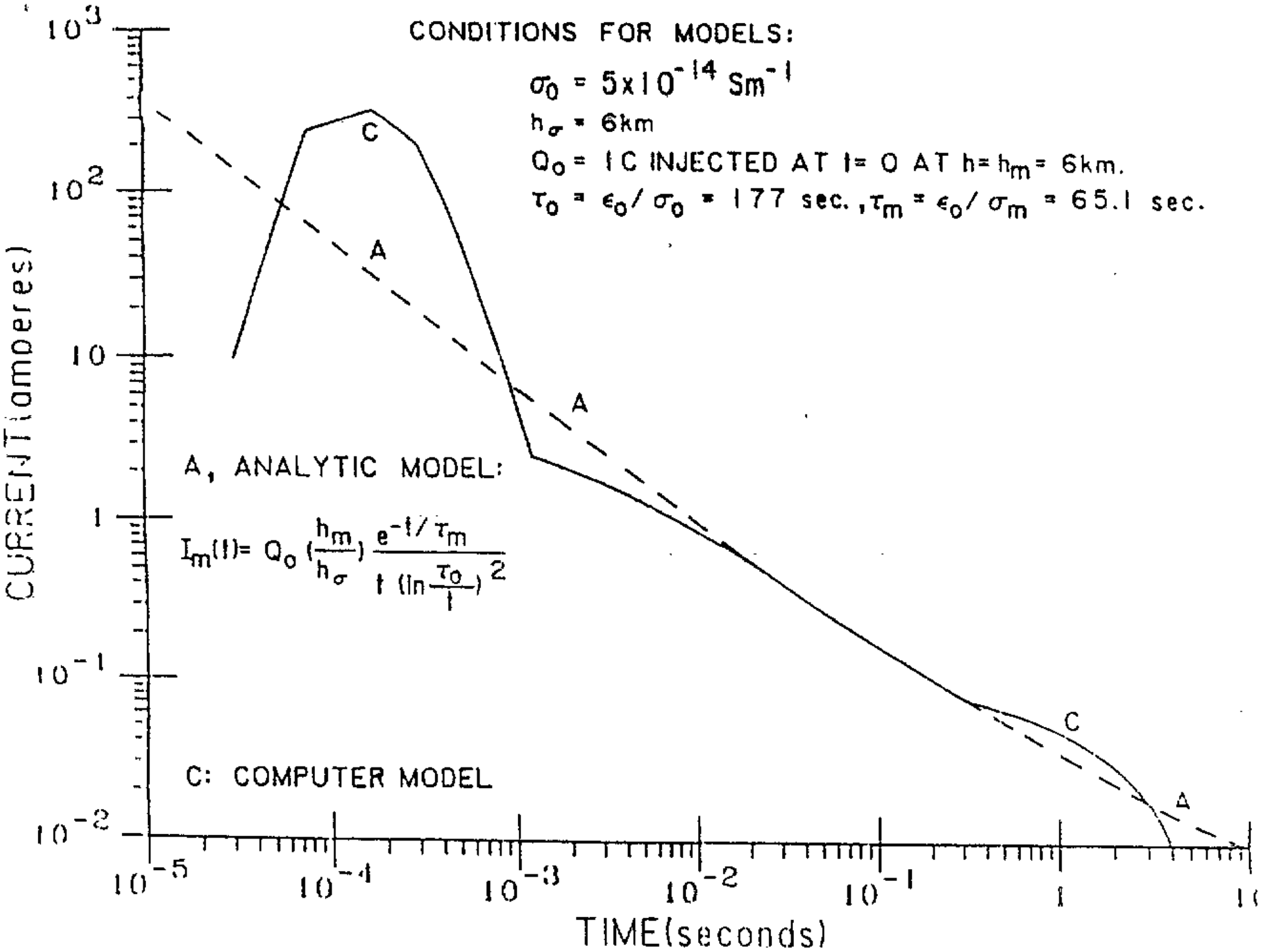
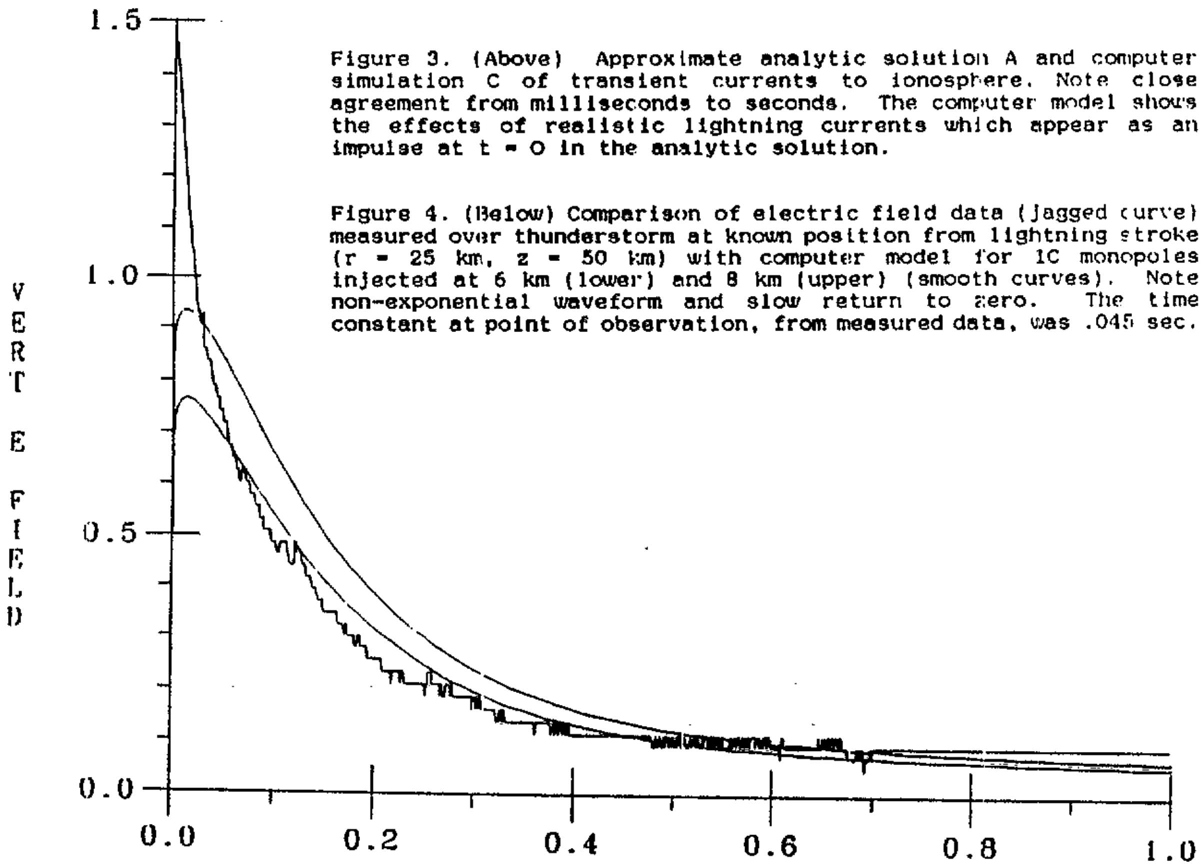


Figure 3. (Above) Approximate analytic solution A and computer simulation C of transient currents to ionosphere. Note close agreement from milliseconds to seconds. The computer model shows the effects of realistic lightning currents which appear as an impulse at t = 0 in the analytic solution.

Figure 4. (Below) Comparison of electric field data (jagged curve) measured over thunderstorm at known position from lightning stroke (r = 25 km, z = 50 km) with computer model for 1C monopoles injected at 6 km (lower) and 8 km (upper) (smooth curves). Note non-exponential waveform and slow return to zero. The time constant at point of observation, from measured data, was .045 sec.



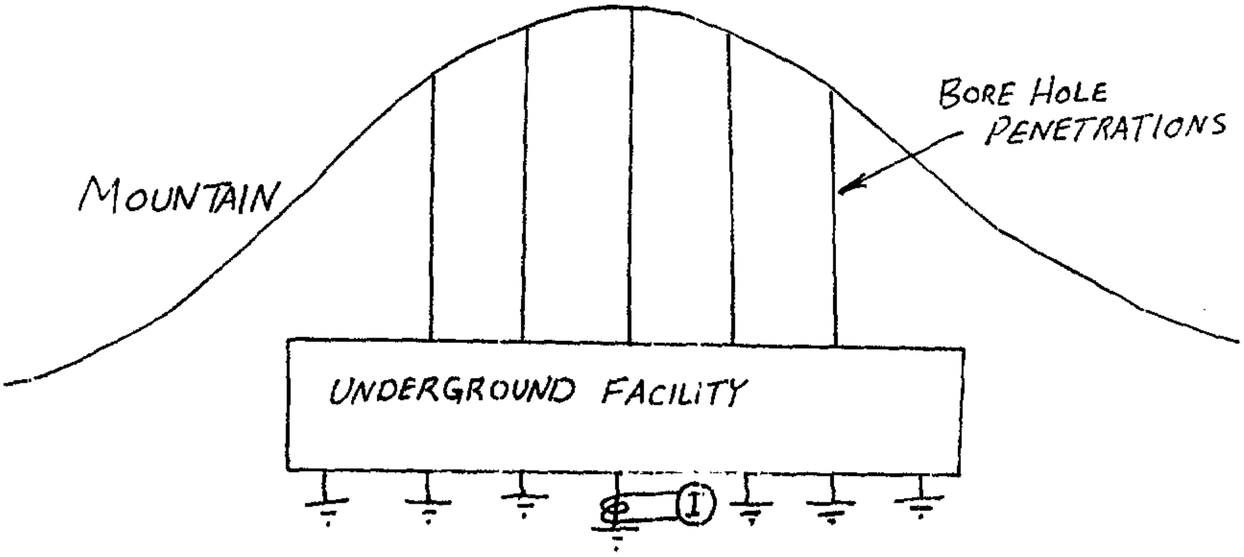
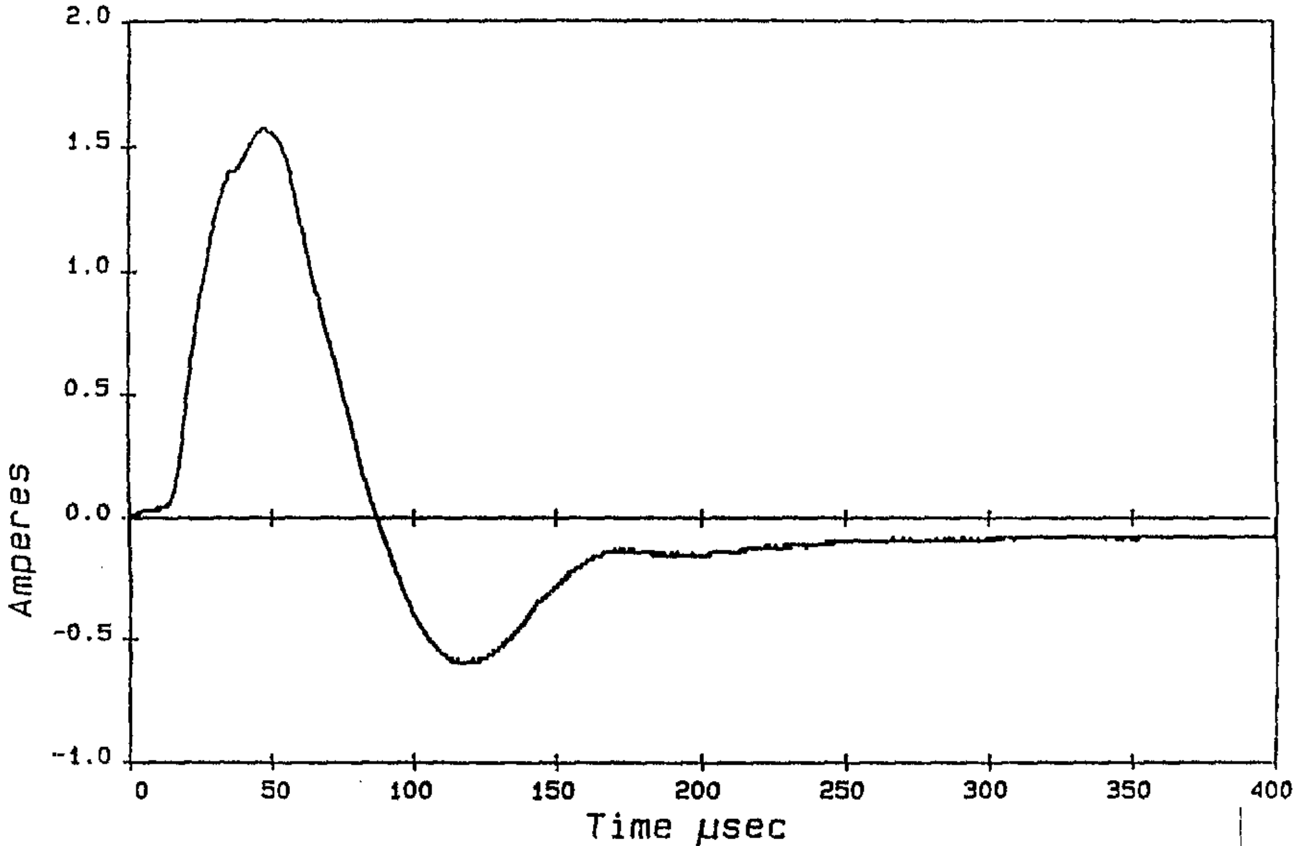


Figure 5. Simplified schematic of underground facility deep inside mountain. Metallic connections are through 'bore holes' from top of mountain. Current to one of numerous parallel 'ground' connections was measured with Rogowski coil and digital transient 'grabber.'.



RESPONSE ASSOCIATED WITH ELLH EVENT: RANGE: 21.9 MI, 35.0 KM AZ: 58.6 DEG.
44.0 MI, 70.0 KM AZ: 73.4 DEG.

Figure 6. Typical currents on ground line of facility of Figure 5 from lightning tens of kilometers distant (two candidate strokes). Pulser calibrations indicated that total current to facility was approximately 100X larger. Current magnitudes and durations were orders of magnitude greater than predicted by LEMP codes.

LIGHTNING HAZARDS STUDY

OL-B, 2d WEATHER SQUADRON
KIRTLAND AFB, NM

PROJECT SUMMARY

The Weapons Laboratory's Nuclear Technology Requirements Division (WL/NTSWR) is studying triggered lightning as a legitimate environmental threat to the reliability of several new strategic ballistic missile systems, one of which is the Peacekeeper. They requested the following information: (1) frequency and duration statistics of several NASA/USAF lightning launch constraints (LLC) used at the Kennedy Space Center applied to 16 Air Force bases in the central and western United States, and (2) frequency of cloud-to-ground (CG) lightning strikes for the same locations. NTSWR wants to incorporate the weather information into a formal WL report which they will then present to the Peacekeeper safety subgroup. The goal: initiate lightning tests and possible design changes on the Peacekeeper. They may also brief SAC commanders about the possible effects on the reliability to the missile. The USAF Environmental and Technical Applications Center completed the statistics on the LLCs and has sent us preliminary results on the CG statistics. We are working with NTSWR to specify final presentation format and are also investigating current published and on-going research of triggered lightning.

OL-B, 2WS (WL/WE)

LIGHTNING HAZARDS STUDY

Captain Andrew J. Terzakis

Kirtland AFB NM

A244-0451

** This Briefing is Unclassified **

OL-B, 2WS (WL/WE)

OVERVIEW

- Background
- Weather Support Requested
- OL-B, 2WS Support
- USAFETAC Support
- Data Limitations
- Preliminary Results
- Questions/Concerns

OL-B, 2WS (WL/WE)

BACKGROUND

- Ballistic Systems Division (BSD)
  - -- dropped all lightning tests on the Peacekeeper missile
- WL/NTSWR, Weapons Laboratory Nuclear Systems/Surety Division
  - -- works with BSD to define hazardous warhead environments
  - -- concerned no lightning tests done on the Peacekeeper
  - -- considers triggered lightning a legitimate hazard

OL-B, 2WS (WL/WE)

-- present weather results to BSD and Peacekeeper safety subgroup

--- emphasize triggered lightning threat

--- initiate testing and/or design changes

-- Possibly brief weather results to SAC commanders

--- reliability issue

OL-B, 2WS (WL/WE)

WEATHER SUPPORT REQUESTED

- Under what conditions will missile launches initiate lightning strikes?

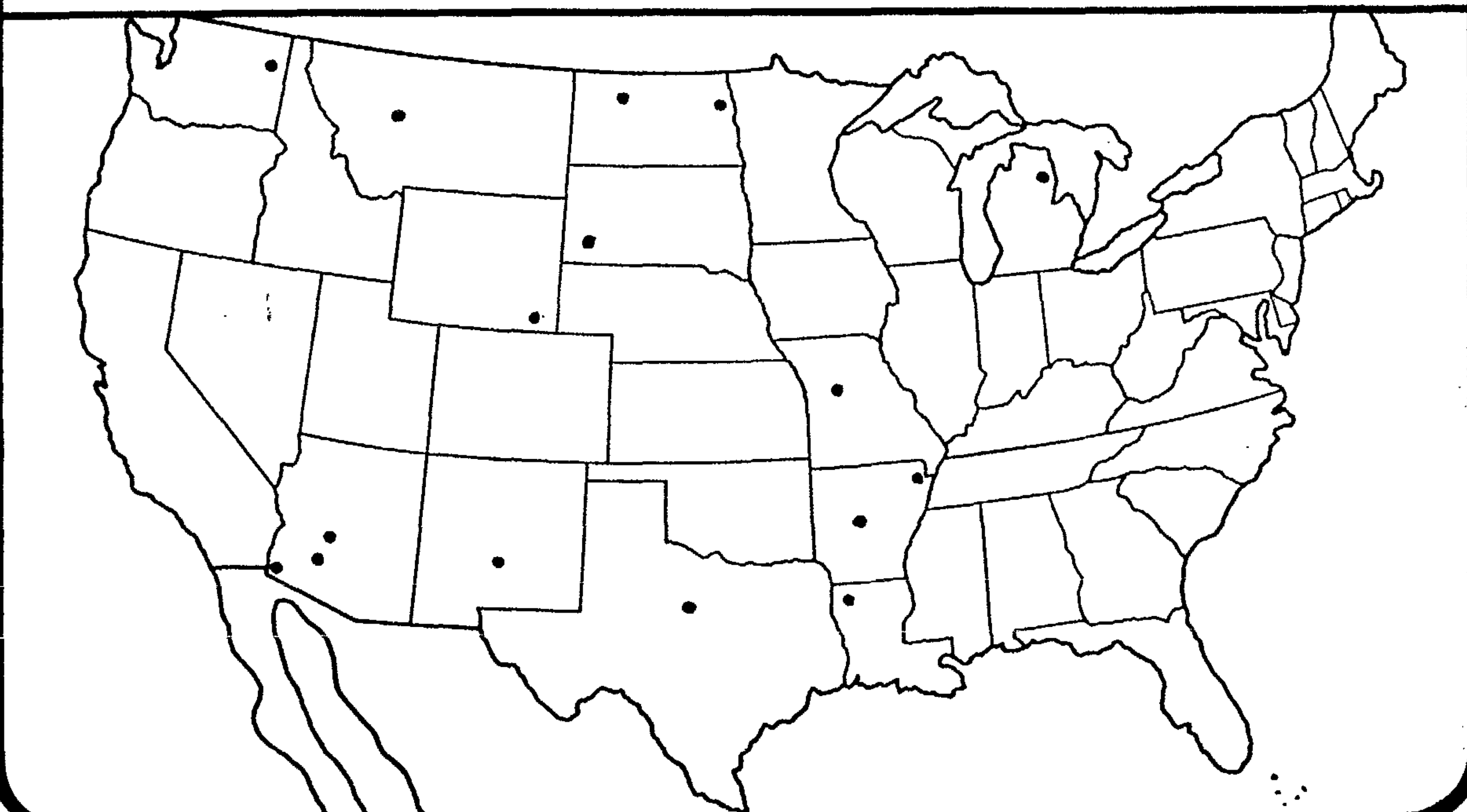
- How often do the conditions exists over current and proposed missile launch fields?

  -- frequency and duration

- Current focus: F.E. Warren AFB

OL-B, 2WS (WL/WE)

STUDY SITES



OL-B, 2WS (WL/WE)

OL–B SUPPORT

- use several current NASA/USAF lightning launch constraints (LLC)
  - -- apply to 16 Air Force bases
  - -- focus on frequency of occurrence
- also use frequency of occurrence of cloud-to-ground strikes, same locations
- ultimately attempt to determine probability of a lightning strike

OL-B, 2WS (WL/WE)

LIGHTNING LAUNCH CONSTRAINTS

(1) through cumulus clouds, tops > 5C level

(2) through/within 5 NM cumulus clouds, tops > −10C level

(3) through/within 10 NM cumulus clouds, tops > −20C level

(4) through/within 10 NM CB or thunderstorm

(5) 4500 ft thick cloud, where temperature between 0C and −20C levels

(6) any clouds extending to/above 0C level and associated with moderate or greater precipitation

(7) through/within 5 NM thunderstorm debris clouds

OL-B, 2WS (WL/WE)

ETAC SUPPORT

- Triggered Lightning
  - used 4 databases tested against each launch constraint for each site
    - 16 yr SFC POR, 1973-1988
    - 5 yr SFC POR, overlaps RTNEPH POR, 1984-1988
    - 5 yr RTNEPH
    - combined SFC-RTNEPH, 1984-1988
  - provided frequency and duration statistics
  - results received: June 1989

OL-B, 2WS (WL/WE)

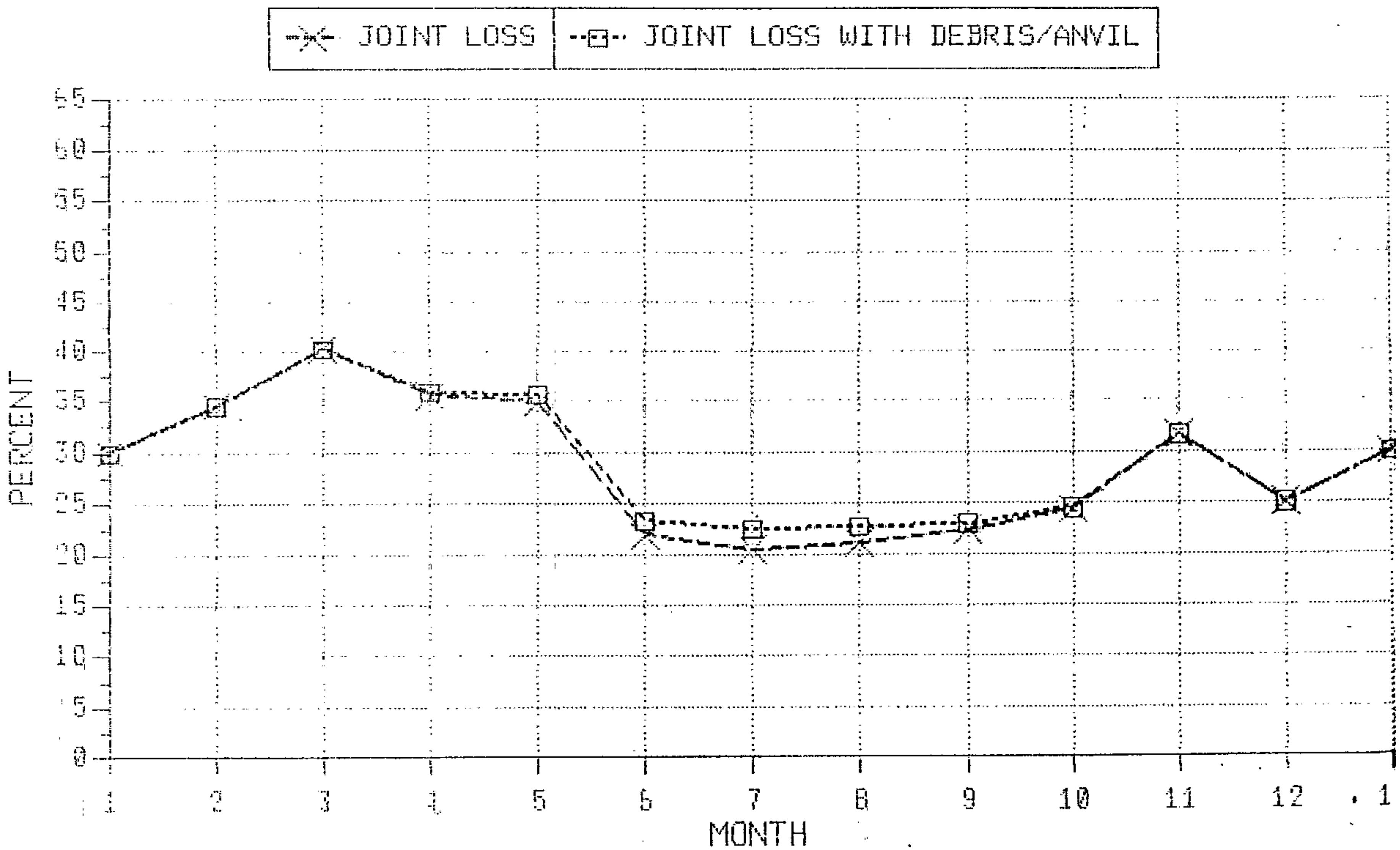
- Cloud-to-Ground Lightning
  - -- using NSSL, BLM, and SUNY data
  - -- compute frequency statistic for each site
  - -- working now with OL-B on output format
  - -- results available: 15 March 1990

OL-B, 2WS (WL/WE)

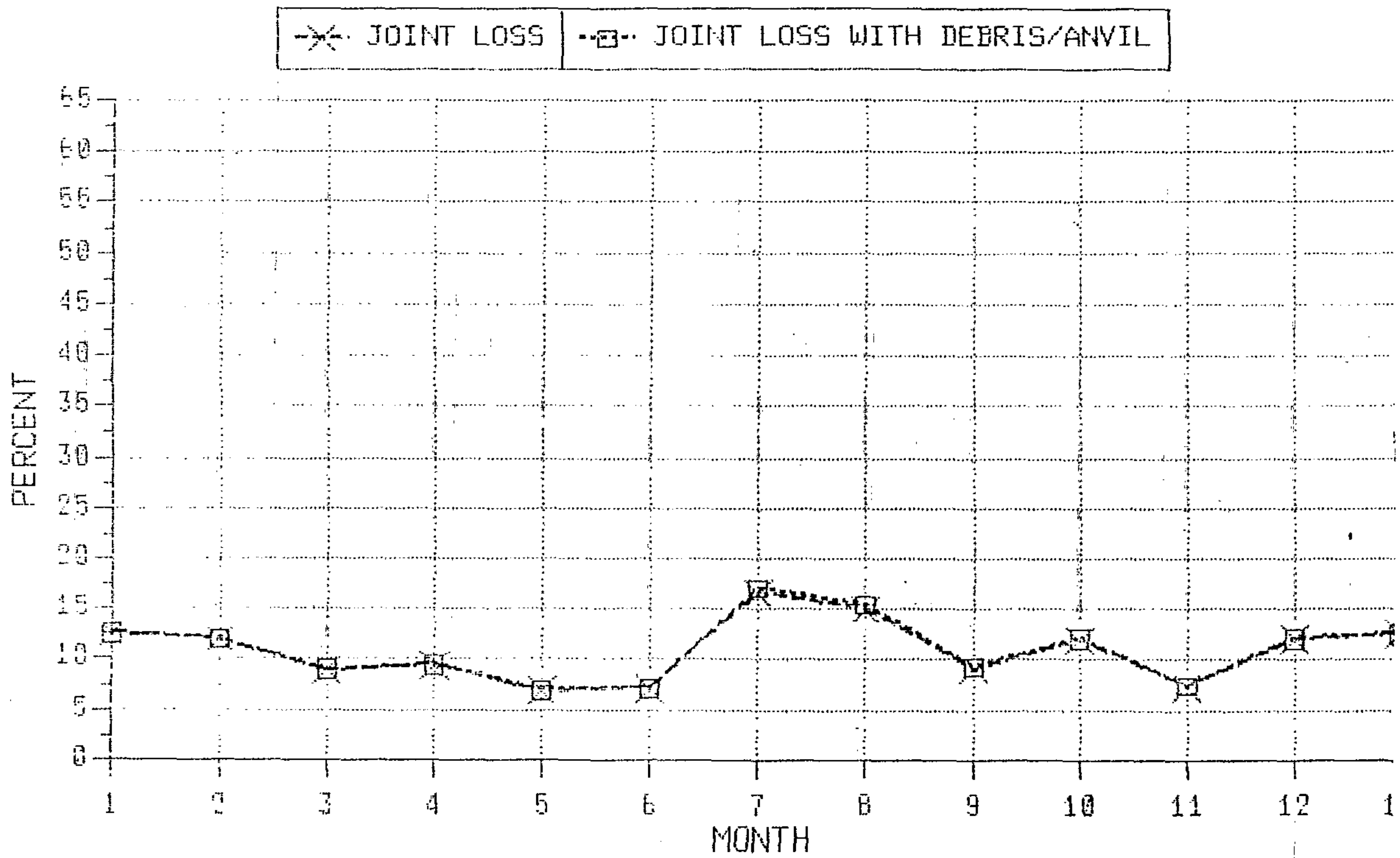
DATA LIMITATIONS

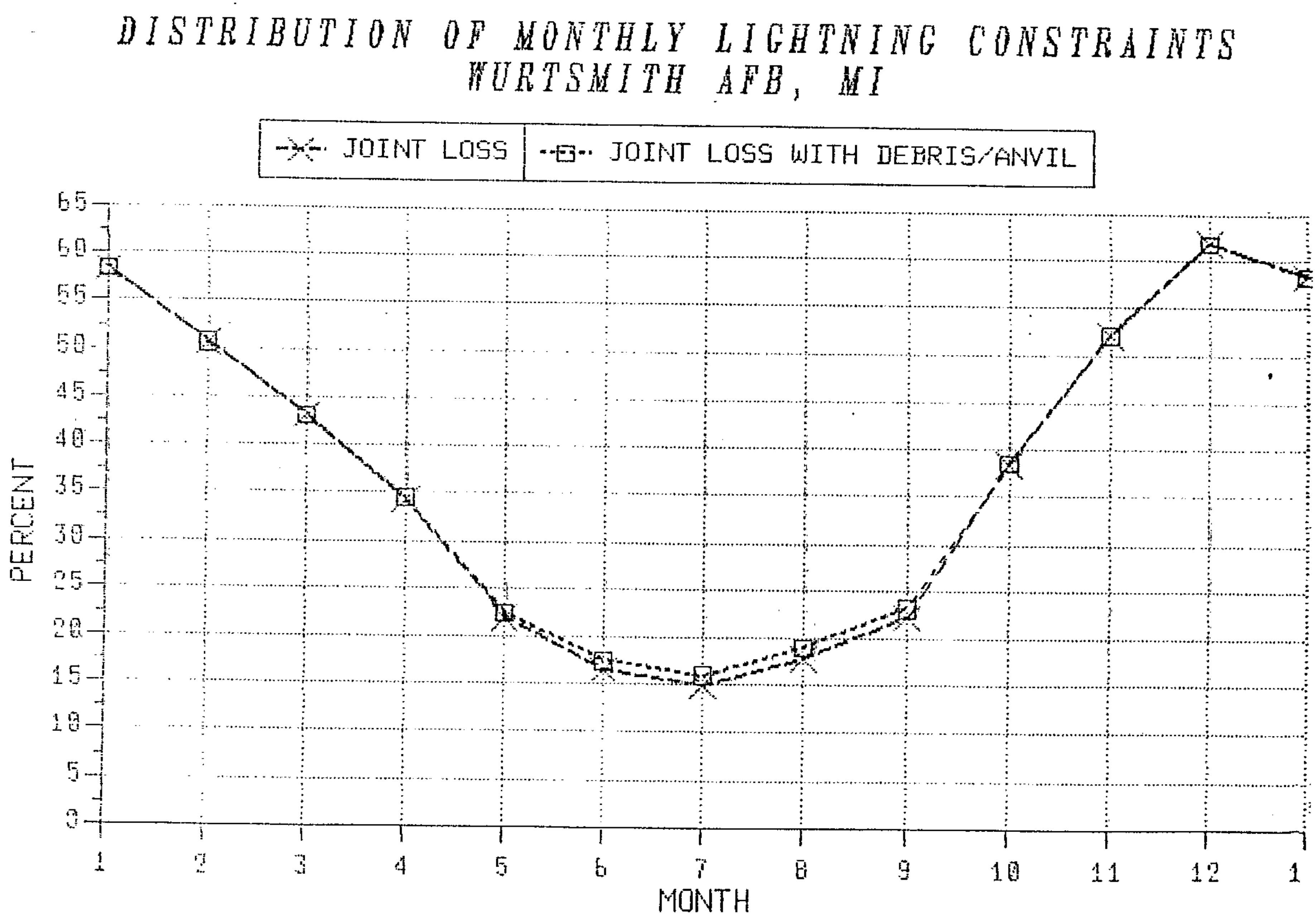
- Surface data limitations
    - -- cloud type and base height data only available every 3 hours (LLC rely on cloud observations)
    - -- observations not geared to anvil/debris cloud reporting
- RTNEPH data limitations
    - -- temporal frequency of satellite passes
    - -- default cloud thickness values used to estimate missing tops
- Upper-air data limitations
    - -- temporal and spacial

DISTRIBUTION OF MONTHLY LIGHTNING CONSTRAINTS
FE WARREN AFB, WY



DISTRIBUTION OF MONTHLY LIGHTNING CONSTRAINTS
YUMA, AZ





DISTRIBUTION OF MONTHLY LIGHTNING CONSTRAINTS
WURTSMITH AFB, MI
JOINT LOSS
JOINT LOSS WITH DEBRIS/ANVIL
PERCENT
MONTH
65
60
55
50
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
1

OL-B, 2WS (AFWL/WE)

QUESTIONS/CONCERNS

- LLCs overly conservative
- valid to apply them at locations other than Kennedy Space Center?
- how to relate 100% probability of lightning conditions to a strike
- observation techniques not developed for this type of study
- missile geometry and plume enhancement of local electric field
- state-of-the-art

LIGHTNING DETECTION AND SENSING ON THE NEVADA TEST SITE

by Carven A. Scott

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

NOAA

U.S. DEPARTMENT OF COMMERCE

NATIONAL WEATHER SERVICE
NUCLEAR SUPPORT OFFICE

LAS VEGAS, NV

February 27, 1990

LIGHTNING DETECTION AND SENSING ON THE NEVADA TEST SITE

by Carven A. Scott

I. INTRODUCTION

Real-time lightning products from the Bureau of Land Management Automatic Lightning Detection System (BLM/ALDS) have been available to the Weather Service Nuclear Support Office (WSNSO) forecasters via the AFOS communications loop (Rasch and Mathewson, 1984) for several years. The lightning data has provided vital storm information in the western U.S. where radar coverage is sparse.

However, these lightning products are only available, at a minimum, every 15 minutes. This interval is unsatisfactory to provide timely support of operations at the Nevada Test Site (NTS). To ensure maximum protection of personnel and equipment, WSNSO activated an ALDS at the NTS in July 1986.

As part of the effort to promote lightning safety on the NTS, an attempt was made to verify the accuracy and detection efficiency of ALDS. The project, Lightning Identification and Verification Evaluation Studies (LIVES), also explored new lightning detection technology, and diverse means of disseminating the information. The evolution of the NTS ALDS, and LIVES will be discussed in this report.

II. ALDS DESCRIPTION

The NTS network consists of seven Direction Finders (DF's) and an Advanced Position Analyzer (APA) manufactured by Lightning Location and Protection, Inc of Tucson, Arizona (Krider, et al, 1976 and Krider et al, 1980). Figure 1 shows the locations of the four original DF's located at the four corners of the NTS, as well as the three senors added during the past year.

Raw DF data is transmitted via dedicated phone line to Las Vegas, NV. There raw data is captured by the Automated Lightning Alert System (ALAS), and relayed to the APA for processing (figure 2). The APA then computes flash location utilizing input from at least two DF's. The optimization routines in the recently upgraded APA attempt to minimize most of the errors that occur in normal triangulation (LLP, 1988).

Processed lightning data is broadcast to display terminals at WSNSO, and across the NTS and TTR. The lightning data is also transmitted to one of WSNSO's minicomputers for archival to hard-disk.

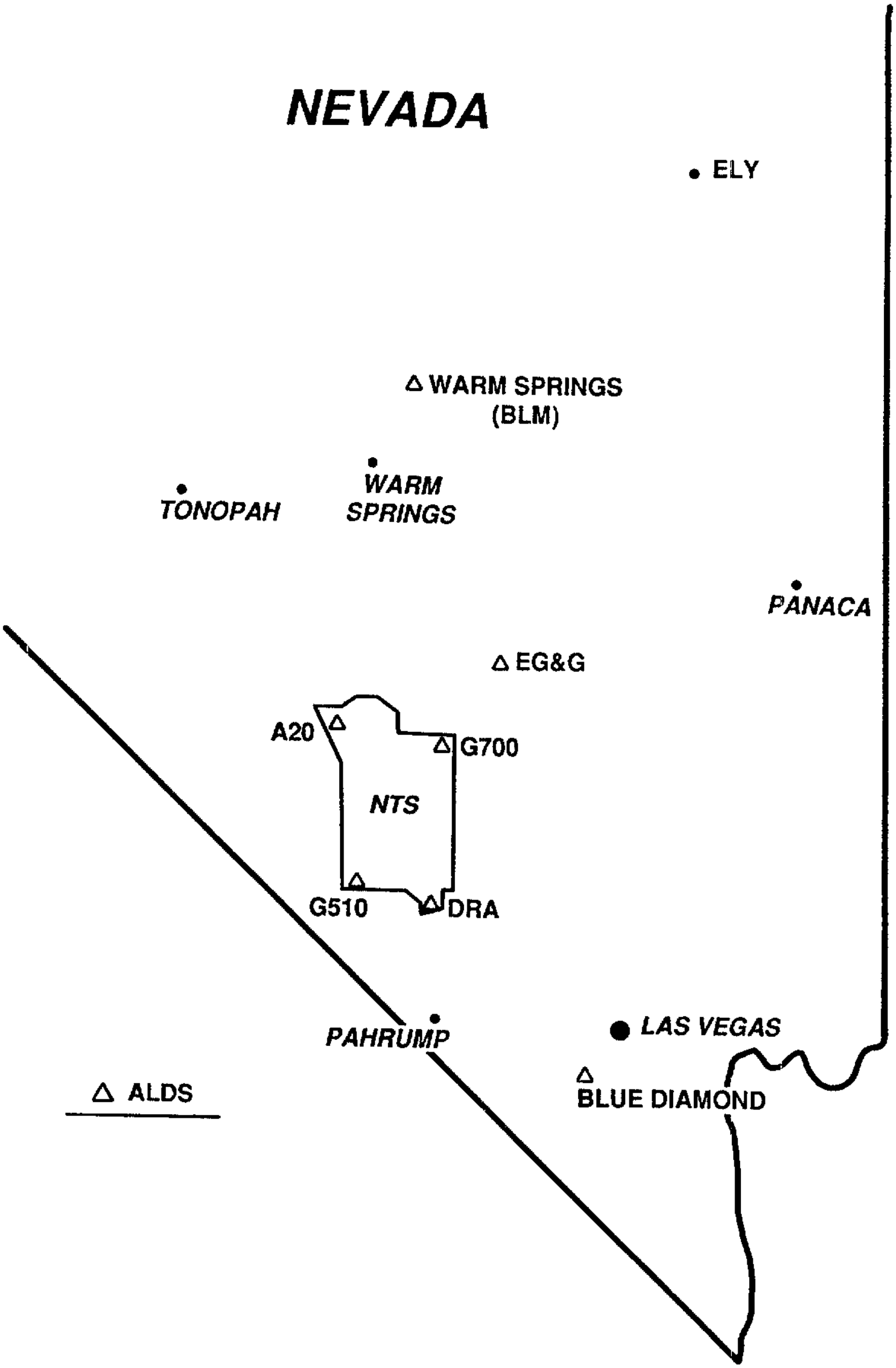


FIGURE 1
NTS ALDS NETWORK

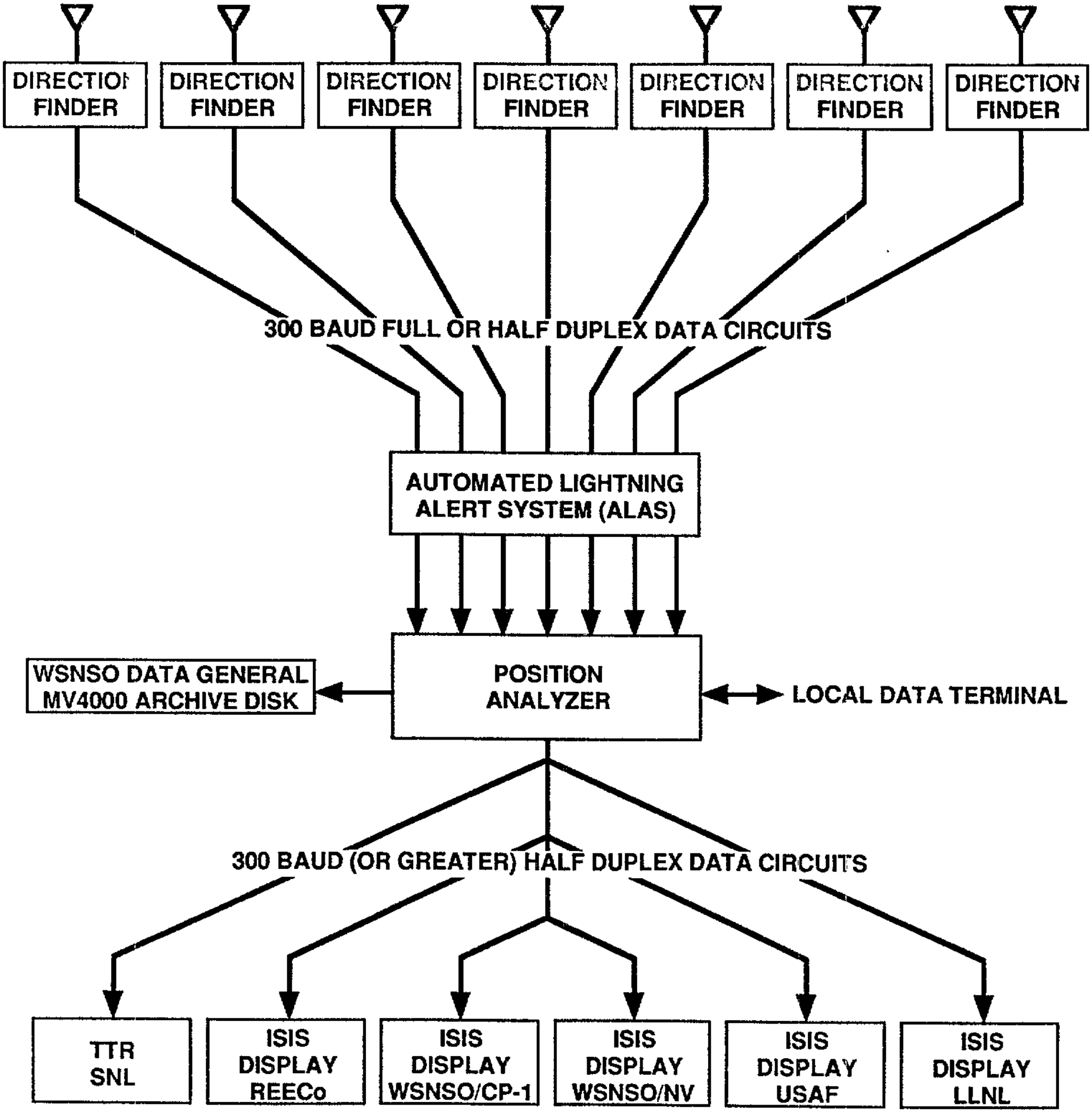


FIGURE 2
NETWORK CONFIGURATION FOR THE NTS LIGHTNING LOCATION SYSTEM

III. LIVES

A. Study Description

Various studies have been conducted over the past few years to evaluate ALDS effectiveness in detecting cloud-to-ground (CG) flashes (Mach 1984, Orville 1987, and MacGorman and Rust 1988). Results from the studies show that the efficiency may vary from 50 to 90 percent depending factors such as network configuration, local electromagnetic noise, etc.. Estimates of location errors range from about 10 km to as much as 60 km, depending on the same factors noted previously.

A rigorous field evaluation study, and operational meteorological research project was attempted on the NTS during the past three summers. The investigations were carried out to validate the NTS ALDS, and to employ new lightning detection technology. The studies were conducted during the afternoons of potential thunderstorm days during what is termed the "monsoon" season in southern Nevada.

Meteorological Technicians were deployed with double-theodolites at selected locations around Yucca Flat on the NTS. The observer determined approximate azimuths to the ground location of the flash, and logged the information along with the time in a journal. Field data was then correlated in time, and location with output from the ALDS to estimate the detection efficiency. Location accuracy was more difficult to verify. Ambiguity in bearings to flashes from observers made a large portion of the field data unusable.

B. Results

During the field experiment, 350 flashes were observed in, and around Yucca Flat. Of those flashes, 98 were reported simultaneously by the 3 observers. Approximately 85 percent (83 of the 98 flashes) were recorded coincidentally by field observers, and the NTS ALDS. Conversely, 15 of the 98 flashes were rejected by the ALDS as invalid. All of the flashes resolved possessed negative polarity.

As stated previously, ambiguity in the field data made determination of location accuracy nearly impossible for most of the flashes. Locations of only ten flashes were known with sufficient confidence to be included in the study. Of the ten flashes, errors in flash location ranged from a minimum of 0.5 km to about 4 km. The average error in flash location was 1.3 km.

The NTS ALDS detection efficiency and accuracy compares very well with similarly configured systems. The field study also reveals that the NTS ALDS performance approaches the theoretical expectation on the NTS.

C. The Automated Lightning Alert System (ALAS)

One of the results of LIVES was the identification of a major weakness in ALDS communication links. LLP, Inc. does not distribute software that monitors the link between the user and the APA, or the DF and the APA. This flaw generated ALDS credibility questions among users, as well as WSNSO meteorologists.

The Automated Lightning Alert System (ALAS) was developed to monitor the communications links (figure 2). ALAS notifies the WSNSO Responsible Weather Service Official (RWSO) of any break in communications such that the RWSO may take proper remedial action. ALAS also periodically pulses the APA and the DF's to monitor the health of the equipment. Thus ALAS provides assurance of ALDS status (figure 3) to both the user community and the WSNSO RWSO.

IV. THE OPTICAL LIGHTNING DETECTOR

Results from tests of the optical lightning detector were exciting. The hand-held system (Scott, 1988) provided unparalleled lightning (thunderstorm) detection capability for the meteorological observer at the Desert Rock Observatory and at Nellis Air Force Base. Lightning of all types were as easily observed during both daylight and nighttime hours. This allowed the observer to assess lightning frequency, and distinguish a thunderstorm from a non-thunderstorm. Both of these tasks are difficult at night, let alone during the day. There is little doubt, for those involved in the field test, that the detector would be an invaluable aid for the meteorological observer.

The optical sensing system works by responding to the rapid changes in the photoelectric emission generated by a lightning flash. A band-pass filter tailored to the optical signature of lightning discriminates against most other light variations which are slower and longer in duration. A lens provides a field of view of 20 degrees, or by removing the lens the field of view is 140 degrees.

Since the device operates on a line-of-sight, intra-cloud lightning was detected at ranges of up to 150 km during the daytime. The system also provided up to a 15 minute lead-time from the first intra-cloud flash to the first CG flash. Detection of intra-cloud lightning frequency is important for monitoring thunderstorm development and intensity due to its close relationship to other aspects of thunderstorms such

*****************ALAS STATUS DISPLAY******************

ALL TIMES ARE GMT			AUG 21 20:41:56
LOCATION		STATUS	
DESERT ROCK	DF1:	OPERATIONAL	AUG 21 20:41:30
LATHROP WELLS	DF2:	KAPUT	AUG 21 20:41:30
AREA 20	DF3:	OPERATIONAL	AUG 21 20:41:30
GATE 700	DF4:	OPERATIONAL	AUG 21 20:41:30
BLUE DIAMOND	DF5:	NOT YET INSTALLED	AUG 21 20:41:30
POSITION ANALYZER	:	OPERATIONAL	AUG 21 20:41:29

VERIFICATION OCCURS EVERY 1 MINUTES. AUG 16 16:38:43

USE ESC FOR SYSTEM DISPLAY; THEN STATUS WILL RETURN TO HERE

FIGURE 3
ALAS STATUS DISPLAY

as microbursts and hail (Williams, 1988 and Beuchler, et al, 1989). As a result of the study, several optical detectors were purchased by NTS/TTR interests for field site protection.

V. CORONA CURRENT/ELECTRIC FIELD SYSTEM

Identifying strong electric fields, and thus the potential for CG lightning, is extremely critical for individuals involved with weapons or explosives. Under fair weather conditions, the electric field at the surface of the earth is about +110 volts/meter. As a thunderstorm begins to build, the electric field in the vicinity of the cloud starts to increase in response to electrification processes in the cloud. Thus, the changes in the static electric field can signal the strength and intensity of an approaching storm.

A problem inherent to all surface based electric field measurement devices such as this is the space charge layer. The space charge layer develops near the earth's surface when grounded objects such as people, trees, or antennas go into corona discharge. (Corona discharge occurs when the electric field around exposed conductors becomes so intense the surrounding air becomes ionized, and an electric current flows from that object to neutralize the field). This space charge layer can mask a much larger field strength aloft (Moore and Vonnegut, 1977). Thus, the electric field measured at the surface may appear to be small when it is really large above the space charge layer. This could be dangerously misleading to someone involved in handling explosives, or to anyone in an exposed environment.

Since the intensity of the corona discharge is a function of electric field strength, the electric field can be measured by directly measuring the corona current. In the past, the corona detector has generally been ignored as an operational tool due to inherent limitations. These limitations (no response below a field strength of 1000 volts/meter, and wind dependence), however, have been overcome utilizing new instrumentation developed by Dr. Ralph Markson of Airborne Research and Associates.

WSNSO has deployed these new corona detectors to assess their viability in an operational environment at the NTS. Figure 4 shows the spatial layout of the four sensors in Yucca Flat. A fifth sensor, a radioactive probe located near the weather office, is utilized as a calibration device.

Figure 5 shows the schematic of the AC/DC system employed on two of the platforms. The AC current "drives" adjusts, and "drives" the probe into corona even during "fair weather" fields.

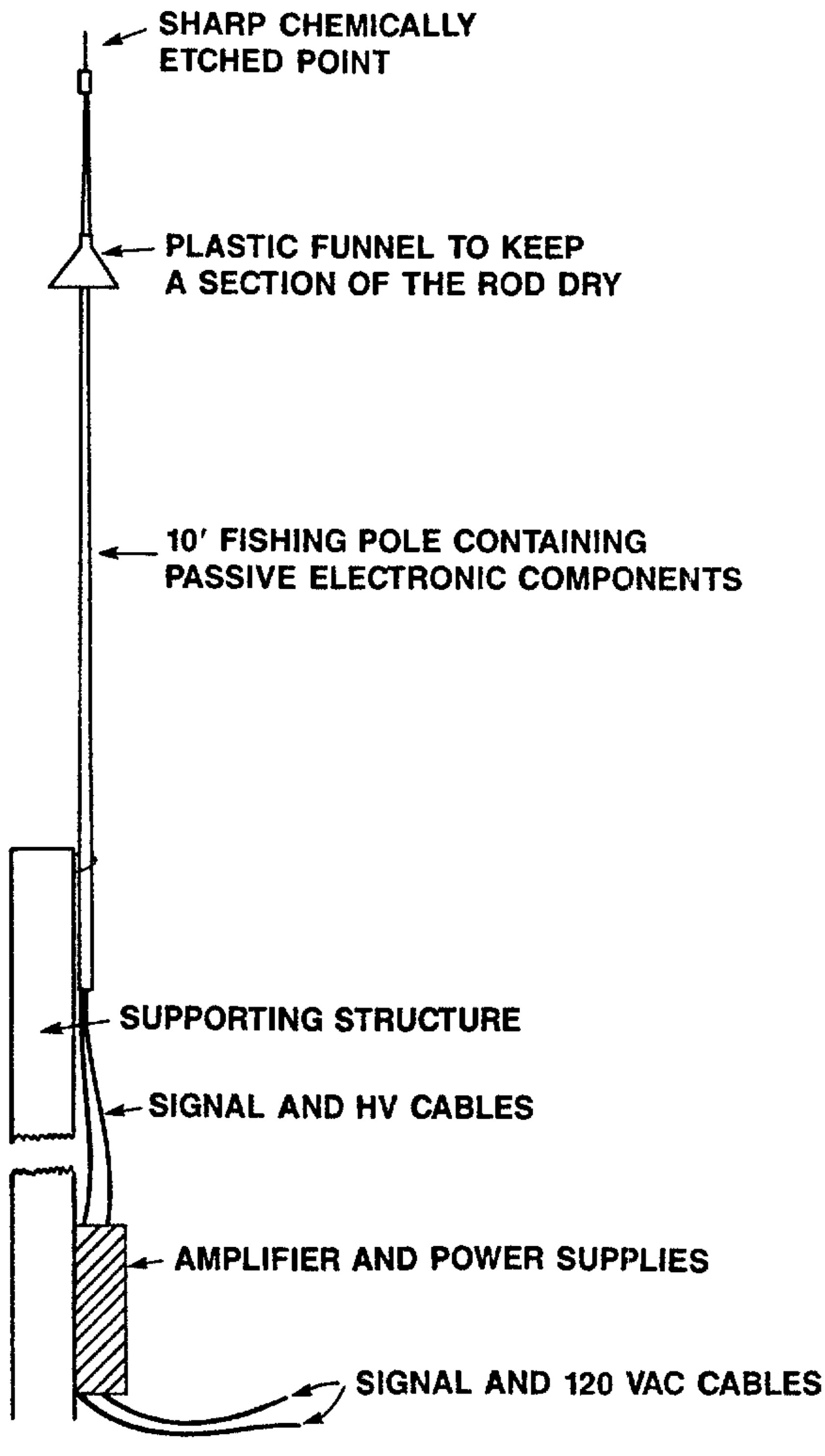


FIGURE 4
CORONA CURRENT SYSTEM COMPONENTS

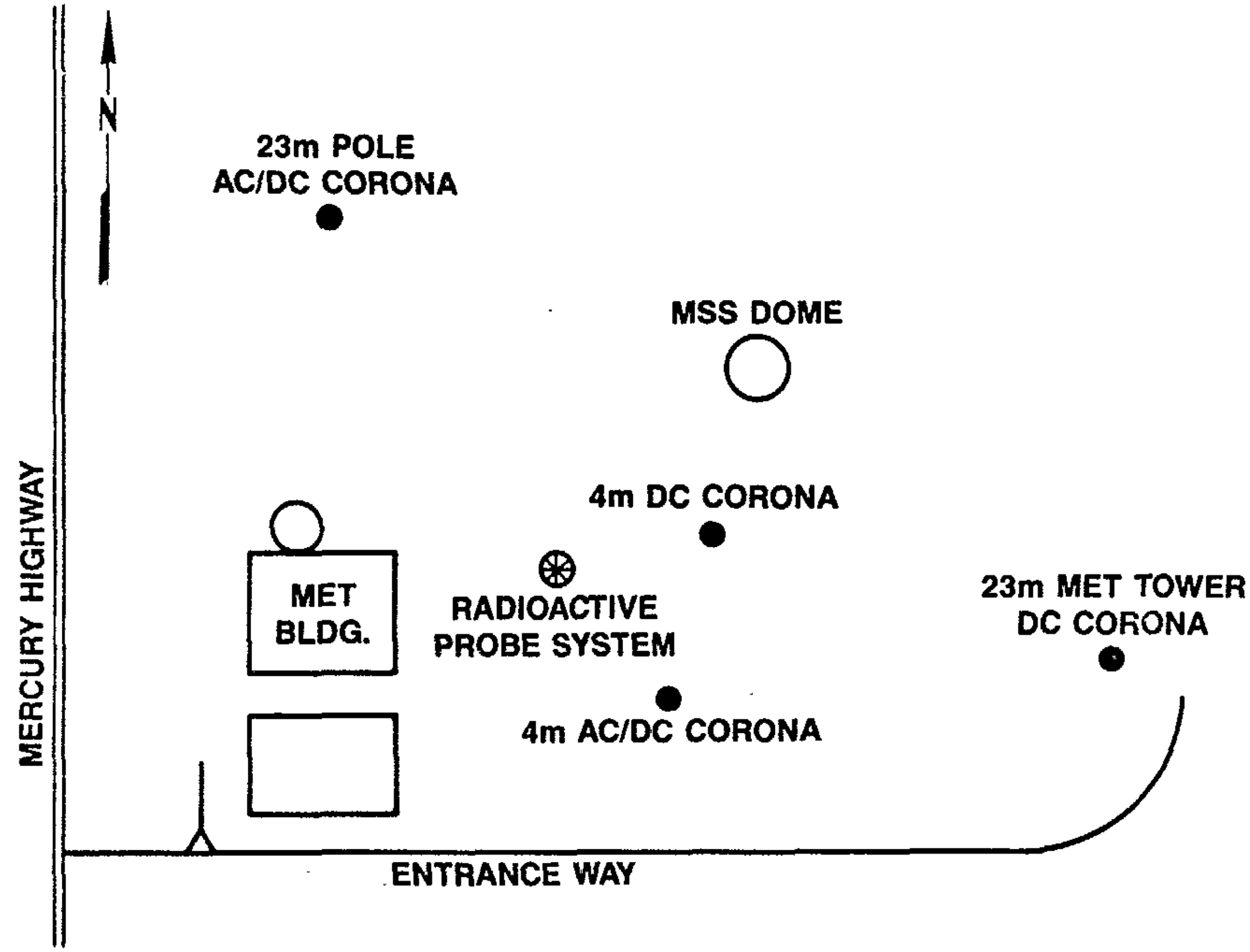


FIGURE 5
DETAILS OF YUCCA FLATS SITE

Analog electric potential data is transmitted to an IBM PC located inside the Yucca weather office. There analog-to-digital cards in the PC convert the signal into a computer-useable form; a statistics/plotting on the PC processes, stores, and displays the data for the user. Based on the proof-of-concept, two NTS/TTR labs purchased similar systems for operational field use.

VI. THE MICRO-ISIS SYSTEM (MISIS)

As part of the lightning safety program on the NTS, the WSNSO duty forecaster issues an ISIS Lightning Advisory (figure 6), warning NTS interests of danger when lightning strikes are recorded within a 20-mile radius of the NTS. WSNSO has been using an LLP Integrated Storm Information System (ISIS) since 1986 to provide this detection service.

Many agencies and private contractors on the NTS have expressed a desire to monitor graphical displays of real-time lightning data from their own locations in the field. Three of these users have purchased their own ISIS displays. However, the cost of approximately $25,000 per unit is prohibitive to many other users who would also like a graphical representation of lightning activity. The total cost for the items necessary to operate MISIS is approximately $5,000.00.

As an alternative to an ISIS display, WSNSO has developed a display system that allows a user's personal computer to dial-in to one of our Data General MV4000 minicomputers. There, a program called Micro ISIS (MISIS) displays limited, ISIS-like displays of lightning strike data on the NTS.

The MISIS system is menu-driven. With it, users can select an overall view of the most recent lightning activity within their choice of either the past 12 minutes or the past two hours. Individual strikes are color-coded to indicate how recently they occurred. Zooming options are also available for a closer view within a 10-, 20-, 30-, or 40-mile radius of selected points.

Other non-lightning data are also available from various submenus. These include worded forecasts and weather observations, as well as graphical displays of winds and temperatures across the NTS.

VII. CONCLUSIONS

There are many opportunities at WSNSO to further increase the operational understanding of the lightning phenomena. Studies

DOELTGNTS
TTAA00 KDOE 222118

LIGHTNING ISIS ALERT SPECIAL WEATHER ADVISORY
WEATHER SERVICE NUCLEAR SUPPORT OFFICE
1010 PM PST 16 JAN 1990

THE NTS ALDS SYSTEM HAS DETECTED LIGHTNING STRIKES WITHIN 20 MILES OF THE NTS AT 2152 PST. CURRENTLY THE ALDS SYSTEM SHOWS ISOLATED GROUND STRIKES AT MERCURY AND NEAR CP1.

THUNDERSTORM MOVEMENT IS TOWARD THE SOUTHWEST AT A SPEED OF 10 MPH.

ISOLATED THUMDERSTORMS WILL CONTINUE TONIGHT AND WEDNESDAY.

INDIVIDUALS ON THE NTS SHOULD TAKE NECESSARY PRECAUTIONS AND LISTEN TO THE RADIO NET. ADDITIONAL STATEMENTS WILL BE ISSUED AS NECESSARY. MONITOR YOUR ISIS DISPLAY.

FOR FURTHER INFORMATION CALL THE WSNSO DUTY FORECASTER AT 295-1255

END FCSTR CEH

FIGURE 6. EXAMPLE OF THE ISIS LIGHTNING ADVISORY

need to conducted comparing the accuracy of a large scale system (BLM/ALDS) with a small scale system (NTS/ALDS). New lightning detection technology such as the optical detector, or the SAFIR system developed in France need to be pursued.

Just as important is the development of better methods of delivering a quality, site-specific product to the end user. WSNSO recently implemented the Meteorological Alert Dissemination (MADS) for this purpose. MADS provides a variety of interfaces (fax, digital voice, dial-in via modem, and cable television) to the DOE family for weather forecasts, watch/warnings, and observations. Upgrades of MADS will include automatic, site-specific, lightning advisory generation.

VIII. REFERENCES

Buechler, D.E., S.J. Goodman, and P.J. Meyer, 1989: Lightning Trends As a Precursor to Microbursts, Preprints of the Third International Conference on the Aviation Weather System, pg 196-201.

Krider, E.P, R.C. Noggle and M.A. Uman, 1976: A Gated, Wideband Magnetic Direction Finder for Lightning Return Strokes. Journal of Applied Meteorology, 15, 301-306.

Krider, E.P., A.E. Pifer and D.L. Vance, 1980: Lightning Direction Finding-Systems for Forest Fire Detection. Bulletin of the American Meteorology Society, 61, 980-986.

Mach, D. M., 1984: Evaluation of an LLP Ground Strike Locating System, Master's Thesis, University of Oklahoma Press.

MacGorman, D. R., and W. D. Rust, 1988: An Evaluation of the LLP and LPATS Lightning Ground Strike Mapping Systems, Proceedings of the 1988 International Aerospace and Ground Conference on Lightning and Static Electricity, pg 235-240.

Orville, R. E., R. A. Weisman, R. B. Pyle, R. W. Henderson, and R. E. Orville, Jr., 1987: Cloud-to-Ground Lightning Flash Characteristics From June 1984 Through May 1985, Journal of Geophysical Research, Vol. 92, No.D5, pg 5640-5644.

Operating Manual: Advanced Position Analyzer User's Guide, Lightning Location and Protection, Inc., October 1988.

Rasch, G. E. and M. A. Mathewson, 1984: Collection and Use of Lightning Strike Data in the Western United States During Summer 1983, NOAA Technical Memorandum NWS WR-184, U. S. Department of Commerce, National Weather Service Western Region.

Scott, C., 1988: The Lightning Verification Project on the Nevada Test Site, Western Region Technical Attachment, No. 88-26, September 6, 1988.

Williams, E.R., M.E. Weber, and R.E. Orville, 1988: The Relationship Between Lightning Type and Convective State of Thunderclouds, Proceedings of the 8th International Conference on Atmospheric Electricity, pg 235-244.

Excerpts from
UCRL-53925

A Lightning Primer

R.T. Hasbrouck

This paper was prepared for the
Range Commanders Council, Meteorology Group
<u>Thunderstorm and Lightning Seminar</u>
Physical Sciences Laboratory, New Mexico State University
Las Cruces, New Mexico
February 27, 1990

February 15, 1990

Lawrence
Livermore
National
Laboratory

Contents

A Lightning Primer

Abstract

This paper is an excerpt from the tutorial *Lightning -- Understanding It and Protecting Systems from Its Effects.* The objective of this paper is to present you with an overview of the atmospheric electrification process and discuss the development and characteristics of lightning discharges. With this knowledge you will be prepared to better understand the presentation dealing with techniques and instrumentation used for lightning threat warning, and detection and tracking.

Introduction

To the lone observer, lightning appears to be a transitory disturbance. On a global scale, however, it is an almost continuous phenomenon—dramatic, costly, and often deadly. For instance, lightning caused the annihilation of a World War I arsenal in New Jersey; it almost turned the Apollo-12 launch into a disaster; it has been responsible for commercial and military aircraft crashes; and it led to the destruction of an Atlas-Centaur launch vehicle in 1987. Lightning also happens to be the number-one weather-related killer in the U.S. Even so, it does not receive the level of attention given to other problems of the environment such as acid rain, the greenhouse effect, and ozone depletion. Folklore mixed with scientific half-truths seem to form the basis for much of the general knowledge about lightning. How many engineers are sufficiently knowledgeable to take it into account in their designs? Instrumentation and control systems, whether ground-based or airborne, are vulnerable to lightning-induced upset and damage.

The awesome visible and audible effects of a good rip-snorting thunderstorm have been a source of fear and wonder ever since humans emerged. While appearing to primitive people as a sign of supernatural vengeance, lightning was very likely responsible for providing their first fires, having previously, perhaps, blasted the primordial soup into the Earth's earliest life forms. Today, in spite of causing significant losses in terms of human life, livestock, equipment, and resources, lightning does perform several important functions. The fires it ignites are known to play an important part in the life cycles of forests, and it makes a significant contribution to global agriculture through its role in nitrogen fixing. (Recent studies indicate that, on a global scale, lightning produces about 5 metric tons per second, or 50% of the total nitrogen oxide produced on Earth.)

Atmospheric Electrification

A good understanding of lightning requires some familiarity with the processes associated with its development, beginning with the phenomenon of atmospheric electricity.

A Bit of History

Looking into the past is interesting and helps to put today's knowledge about atmospheric electricity into perspective. The following, although not complete, does highlight the past accomplishments of some truly brilliant people.

W. Wall (1708) is credited with first suggesting a connection between lightning and thunder, and the flash and snap from the static discharge of a piece of amber. J. H. Winkler (1746) was very close to present-day theories when he suggested that friction and collision of airborne particles was the source of electricity in the air. Using separate methods, and working independently, L. G. Lemonnier and J. de Romas

(1752) almost concurrently discovered atmospheric electrical effects under fair-weather conditions. In France, T. F. D'Alibard (1752) used an elevated iron rod, insulated from the ground, to collect electricity from thunder clouds. Benjamin Franklin had suggested this approach in 1750, but Philadelphia lacked a tower of adequate height. In 1752, Franklin carried out his famous kite experiment, unaware of D'Alibard's success just one month earlier. A year later, Franklin determined that thunderclouds generally exhibit negative charge.

Lord Kelvin applied his significant advances in electrostatic theory to atmospheric electricity as well. In 1860, he first suggested the existence of a conducting, equipotential layer in the upper atmosphere that, in conjunction with the conductive Earth and the global atmosphere, could be likened to a spherical condenser. He also observed that lightning flashes changed the atmospheric potential gradient. Although C. A. Coulomb (1795) and C. Matteucci (1850) determined that air was an electrical conductor, it was F. Linss (1897) who calculated that this conductivity should cause the Earth's charge to leak away in about 10 minutes! Said leakage notwithstanding, the Earth maintains its negative charge, a fact that has prompted much research into atmospheric electrification.

It wasn't until 1932 that B. F. J. Schonland presented the connection between atmospheric electrification and Kelvin's conducting layer. He also differentiated between the conducting layer and the higher-altitude Heaviside layer. The conductivity of the former he attributed to "penetrating radiation" (i.e., cosmic rays), and the latter to solar radiation. These layers became known, respectively, as the *electrosphere* and the *ionosphere*.

Into the Present

As the 20th century progressed, measurements made using sounding balloons confirmed the high conductivity of the upper atmosphere (40 to 60 km above the Earth), reinforcing the concept of the electrosphere. Since Kelvin's global condenser maintains its electric field, despite the air's electrical conductivity, it was recognized that a means for recharging must exist. Conventional *atmospheric electrification* studies identified thunderstorms and other related lower-atmospheric phenomena as the generators. In recent years, rocket-borne instrumentation has led to the discovery that other low-frequency electromagnetic waves, in addition to lightning, contribute to the global electric field. Those that are presently known are tidal winds interacting with the ionospheric plasma at heights of 80 to 200 km (known as the dynamo region) and solar winds interacting with the *magnetosphere* in the region extending beyond 200 km (see Fig. 1). These electrodynamic processes in the ionosphere and magnetosphere modulate the electric currents flowing through the upper portion of the *global circuit* at high geomagnetic latitudes (i.e., $>60°$—the polar cap regions). The study of these and other possible sources of atmospheric electrification falls into the broad category called *atmospheric electrodynamics*.

These points have been mentioned to give an overview of how our atmosphere maintains its charge. However, since this tutorial is principally concerned with lightning, those other effects will receive no further treatment.

Ionization of the Atmosphere

The air in the atmosphere is electrically conductive as a result of ionizing radiation. Over the continents, the primary sources of this radiation are radioactivity in the ground and radon, a naturally occurring radioactive gas that is a decay product of uranium 238. The ions produced extend several hundred meters above the ground. The world's oceans exhibit negligible radioactivity, and thus their role as an ionization source is minimal. The major source of atmospheric ionization, galactic cosmic rays, produces ionization at rates that are functions of height, latitude, meteorological conditions, and solar activity.

The Global Circuit

Atmospheric electrification on the global scale can be represented by the simplified schematic in Fig. 2. Calculations (see Ref. 1, chapters 2 and 3, for details) that take into account the surface area of the

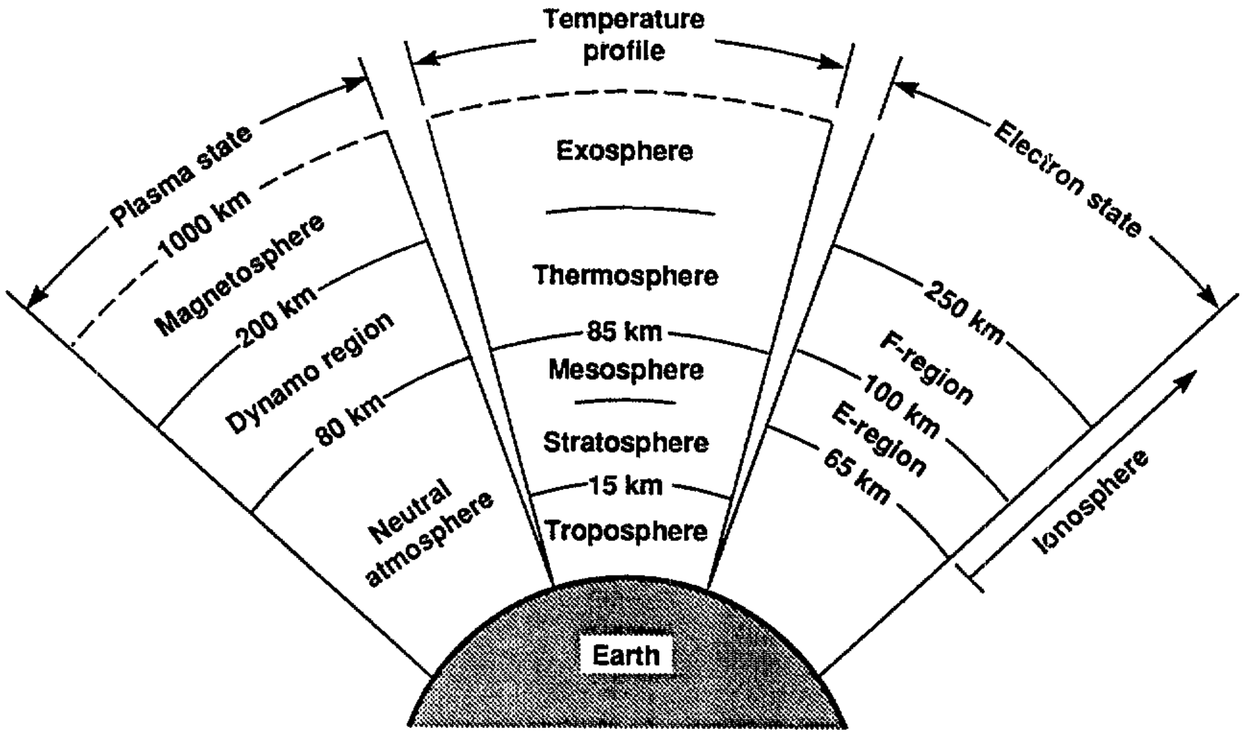


Figure 1. Ways of describing the atmosphere according to its plasma states, its temperature regions, and its electron states.

Earth and the resistance of a column of air between sea level and 100 km (the ionosphere) show the global resistance of the atmosphere to be about 230 Ω. The resistance of the dynamo region (80 to 200 km) has been calculated to be 30 mΩ, and the estimated global resistance of the Earth's surface is about 1 mΩ.

Measurements made in fair weather, far from thunderstorms, show that the Earth carries a negative charge relative to the atmosphere. The current density is -2×10^{-12} A/m^2 and is accompanied by a downward-directed electric field of about −100 V/m at the Earth's surface. This parameter is the *fair-weather electric field,* a vector quantity that is normal to the horizontal, equipotential surface of the conducting Earth. Its algebraic sign is based on convention. Since height is normally considered to be positive in the upward direction, the fair-weather *potential gradient* (expressed in volts per meter) is positive. In electrostatics, the convention is for an electric field vector to point in the direction of movement of a positive test charge. In this case, the test charge moves downward, opposite to the potential gradient, thus giving the *electric field* a negative sign. Prior to the formalization of the discipline of electrostatics, much of the literature dealing with atmospheric electricity used the term "field" when the potential gradient was being discussed. Thus, the fair-weather electric field erroneously inherited a positive sign, an artifact that is still widely used today. In this tutorial, the electric field will carry its proper negative sign.

Atmospheric potential, the average potential between the ionosphere and the Earth's surface, has been measured to be approximately +270 kV (ranging from 180 to 350 kV). The sum of all currents flowing in the Earth's fair-weather regions is about −1 kA. The total charge in the global atmosphere is calculated to be about 677×10^3 C (C = coulombs), with a corresponding capacitance of 2.9 F. The corresponding global time constant is about 11 min. Thus, if atmospheric charging suddenly ceased worldwide, the fair-weather field would disappear in approximately three time constants, or a little over half an hour. In 1897, Linss was reasonably close when he calculated that the conductivity of the air should cause the Earth to become discharged in about 10 minutes!

The final element in this global atmospheric electrical circuit is the generator. At any time, there are approximately 2000 thunderstorms in progress around the planet. As we will see in a later section, lightning is one mechanism for lowering charge to the Earth. Others are conduction current, convection, and precipitation. With a global atmospheric current of −1 kA and 2000 storms in progress simultaneously, it

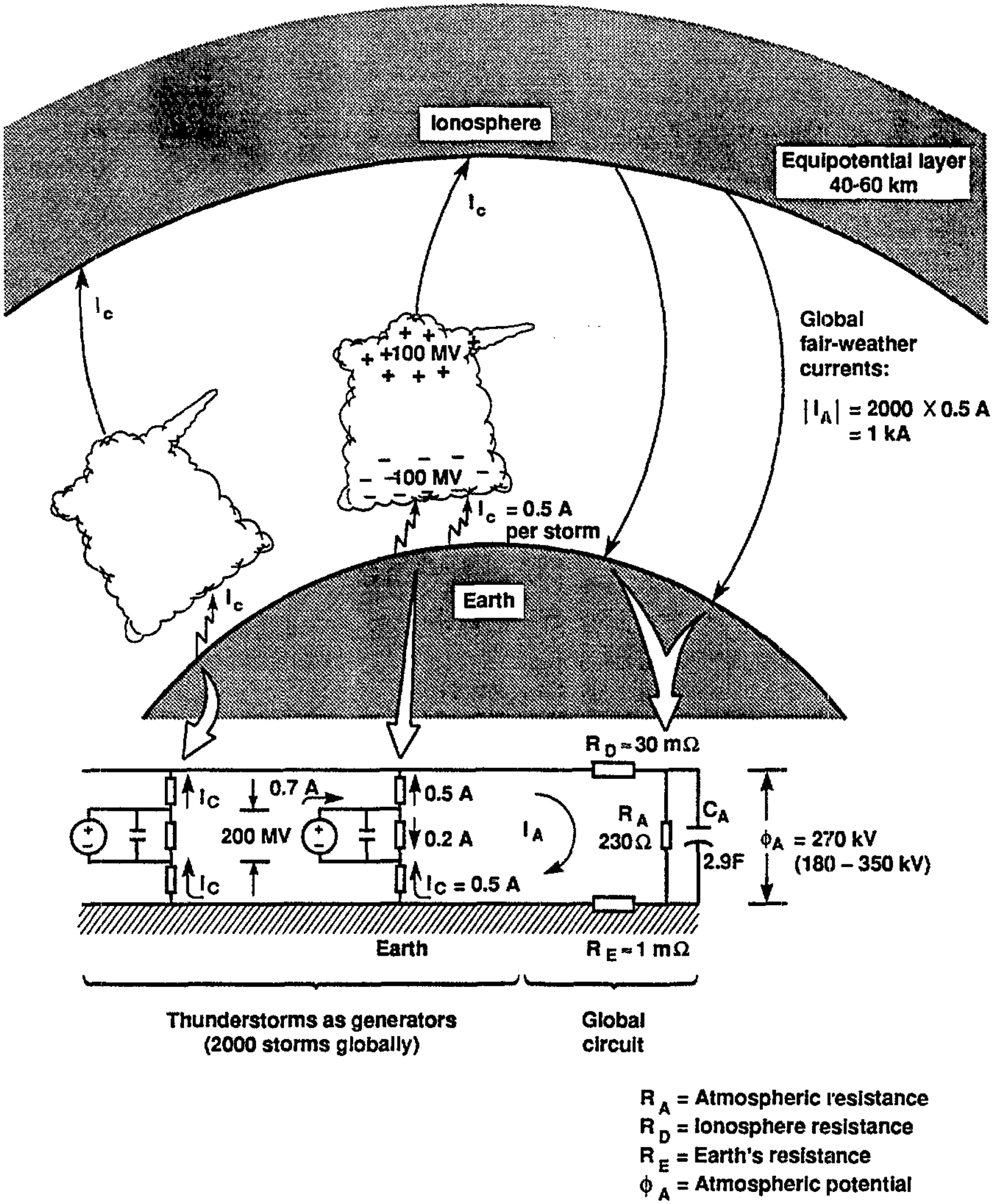


Figure 2. The global atmospheric electric circuit. The two thunderstorms shown act as generators, with the rest of the world completing an RC circuit.

can be seen that each storm should contribute an average charging current of about 0.5 A to the ionosphere. Current in the global circuit is a maximum during the northern hemisphere's winter. The circuit is completed through the 230-Ω global resistance of the planet's fair-weather regions. Within the cloud, the conductive air is responsible for a discharge current of 0.2 A, and the resulting source current of the generator is 0.7 A. Additional calculations show a typical thunderstorm as having a source potential of 200 MV, a capacitance of 1 μF, and electric energy equal to 140 MWhr (for a 1-hr storm).

Thunderstorms

Thunderstorms, the major source of electromagnetic energy in the lower atmosphere, are considered to be the driver of the global circuit. They, in turn, are the result of atmospheric temperature gradients produced by solar heating. For this reason, severe thunderstorms occur most frequently in the midafternoons (1) in the temperate regions during spring and summer and (2) in the tropical regions during the northern winter. Thunderstorms occur around the clock and throughout the year, including the winter months, and are observed beyond the normal bounds of the temperate zones. It is interesting to note that, globally, the greatest number of storms in progress occurs between 1700 and 1800, GMT, which coincides with maximum thunderstorm activity in Africa and South America.

Thunderstorms fall into two catagories: convective, and frontal. *Convective storms* are local in nature, generally developing in place in the mid- to late afternoon. During a relatively short life cycle of one to two hours, they produce moderate to heavy amounts of lightning, rain, wind, and sometimes small hail. *Frontal storms* are well organized and violent, often lasting for many hours. They produce severe lightning activity, large-diameter hail, high winds, and sometimes tornadoes.

Convective storms develop in the atmospheric region known as the *troposphere*, which extends from the surface up to about 15 km. In this region, temperature decreases as the altitude increases. Convective storms require a layer of moist air extending to an altitude of approximately 1 km, strong solar heating of the ground and adjacent air, and an unstable atmosphere (i.e., an ambient temperature that falls rapidly with increasing altitude). Small parcels of moist heated air will rise as long as their temperatures are higher than that of the air through which they pass. Since increasing altitude is accompanied not only by decreasing temperature, but also by decreasing atmospheric pressure, expansion of the parcels takes place. This results in cooling and condensation of the water vapor they contain. The latent heat of condensation released into the parcels causes them to remain at higher-than-ambient temperatures and allows them to continue rising.

The action of rising air parcels leads to the formation of individual, puffy, white, *cumulus* clouds. This is the first stage of the local thundercloud and lasts for 10 to 15 minutes. Gradually, the individual cumulus clouds merge to form a much larger *cumulus congestus* cloud. This cloud, in which all of the air motion is upward, may reach 1.5 km in diameter and exhibit a well-defined top, which rises at a rate of 10 to 30 m/sec.

As this cloud continues to grow, small cloud drops and large water drops are formed. The large drops, now too heavy to be supported by the convective updraft, begin to fall as rain. As the lighter cloud drops continue their rise, ice particles form in the −10 to −20°C region, releasing additional latent heat in the process. Upon reaching the cloud top (10 to 12 km), the −50°C temperature causes ice crystals to form. As they begin to fall back through the cloud's warmer regions, snowflakes may develop (at 5 to 10 km). When supercooled cloud drops freeze on the surfaces of the decending ice crystals, *riming* occurs, with heavy riming producing particles referred to as *graupel*. Passing into the region above the freezing point, the particles melt, joining the rain already in progress. If a temperature inversion (colder temperature) is subsequently encountered, the raindrops freeze, becoming hail pellets.

Condensation occurring in the upper part of the updraft and an increase in air density resulting from rain in its middle region cause the cloud to lose its buoyancy. The thundercloud, or cell (Fig. 3), has now reached the mature stage and is referred to as *cumulonimbus* (CB in meteorological terms). It has a characteristic flattened, anvil-shaped top, which may rise beyond 15 km into the *stratosphere* (where temperature remains constant or increases with altitude). During the 15 to 30 minutes the CB usually lasts, heavy precipitation takes place, accompanied by appreciable lightning and a strong, cold, evaporating downdraft.

The storm moves into its final, dissipating phase when the cold downdraft counteracts the warm moist updraft that has been supplying the cell. (If this downdraft is particularly strong, it is called a

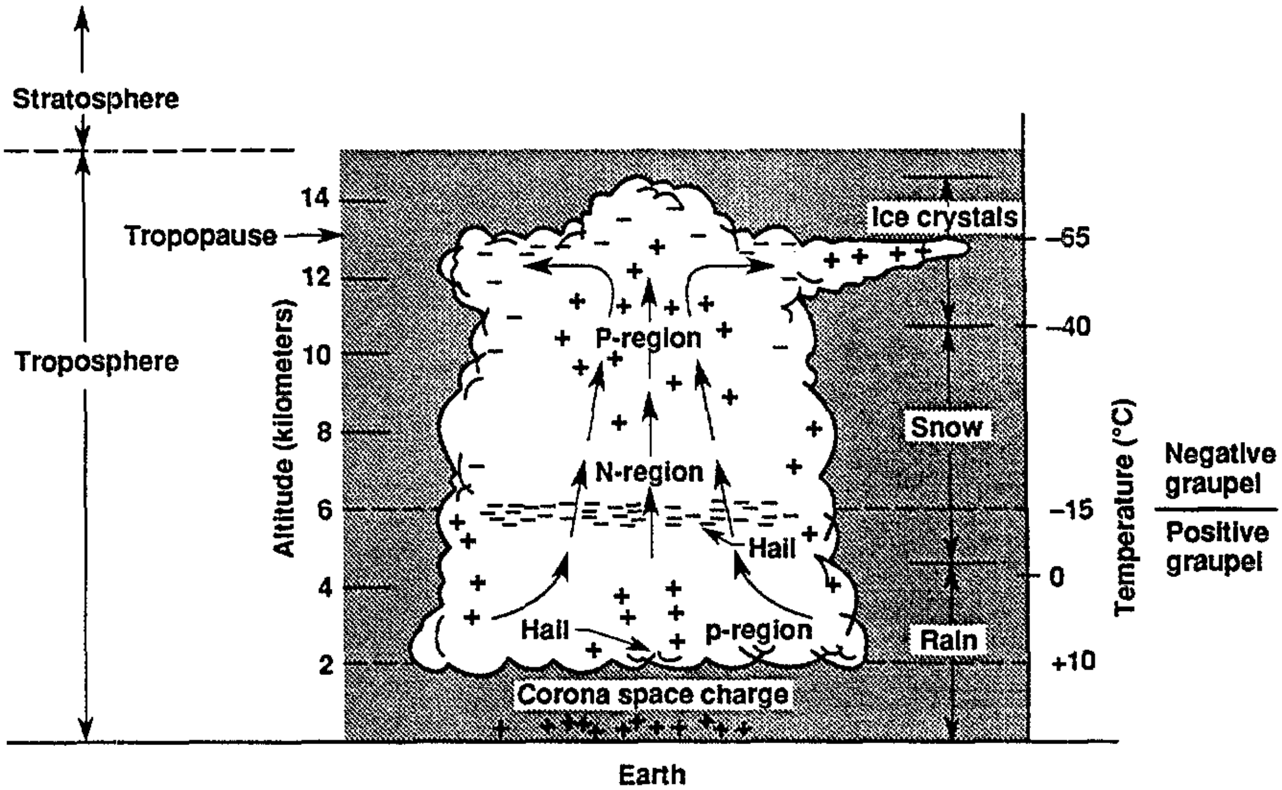


Figure 3. Typical mature thunderhead (*cumulonimbus*). Arrows inside the cloud depict strong updrafts.

microburst, a phenomenon known to be deadly to aircraft in flight.) Precipitation diminishes, and the severe updrafts and downdrafts fall off, as does the lightning activity. After about 30 minutes, the remainder of the water vapor has evaporated, and the cloud has blown away. However, it is not uncommon for more CBs to develop in the same general area when the cold downdraft forces adjacent warm, moist air upward, reinitiating the cell-producing process.

Frontal thunderstorms exhibit the characteristic of self-propagation, generally forming near the boundary of a moving cold front and a region of stationary, warm, moist air. Lacking buoyancy, the cold front moves in under the warm air, pushing it up and generating a cell as described above. The cycle of updraft, followed by downdraft, is repeated as the front moves along. When the winds in the stratosphere are relatively strong and increase with altitude, storms can continue to regenerate, advancing over tens to hundreds of kilometers.

As one might expect, not all thunderstorms follow the same pattern, and the details of their formation continues to be studied. Severe thunderstorms develop under meteorological conditions that are different from those associated with a local storm. Often, prior to the onset of thunderstorms, a warm, dry layer of air in the stratosphere forces the moist air to remain close to the surface. This causes the stationary layer to absorb heat and become even more humid. When the cold front arrives and pushes its way under the stationary layer, its force overcomes that of the stratospheric layer, and the humid air rises. The violent formation of thunderstorms ensues, producing severe lightning, large-diameter hail, and winds exceeding 100 km/h.

Cloud Electrification

When we see lightning and/or hear thunder, we are observing the manifestations of a dramatic and sudden charge transfer on the order of 10 C (median value). This transfer, the charge carried by 10^{20} electrons, occurs in a few hundred milliseconds. For this to take place, the cloud must be polarized (i.e., separate regions of positive and negative charge must exist). In a simple cloud model, these two vertically separated regions form a dipole, with the negative pole located nearest the Earth. Fairly recent studies have cleared up an ambiguity first identified by Franklin's observation that, although thunderstorms generally exhibited negative charge, positive charge was sometimes detected. In the 1920s, separate experiments by C. T. R. Wilson (of cloud-chamber fame, and the first to determine the amount of charge in a thunderstorm cloud) and G. C. Simpson arrived at opposite conclusions regarding whether the dipole was negative or positive. In the 1960s, it was determined that the polarity measured depends on where the measurement was made relative to the cloud's charge centers (i.e., directly under the cloud or at some distance away from it). In addition, a small region of positive charge (*p-region*) was found to exist in the bottom of the cloud, resulting in a tripole rather than a dipole.

Polarization, the result of charge separation within the cloud, is now an accepted concept within the atmospheric science community. However, the microphysics of *charge separation* has been and continues to be the subject of much research—and disagreement. The difficulty of arriving at a completely acceptable theory is attributable, in part, to the fact that the study of lightning and thunderstorm physics extends from atomic levels (10^{-13} km) to the atmospheric dynamics of a thundercloud (tens to hundreds of kilometers). Without delving into the many details associated with charge-separation theories, the salient points of two different hypotheses, convection and precipitation, will be discussed briefly.

The *convection hypothesis* suggests that positive charges released from objects in corona discharge at the Earth's surface are carried to the upper portion of the cloud by the warm-air updraft. Negative ions produced above the cloud by cosmic rays are attracted to the positively charged, upper portion of the cloud and attach themselves to cloud particles, creating a negative screening layer. Downdrafts then transport the negative charges to the lower part of the cloud. (The p-region might be a positive screening layer resulting from the attachment of positive corona ions to cloud particles.) Note that precipitation is not considered.

In the *precipitation hypothesis*, gravity pulls precipitation particles (i.e., raindrops, hailstones, and graupel) downward through the cell. Negative charge is transferred to the precipitation particles when they collide with the lighter cloud drops and ice crystals, which are suspended in the updraft. Now positively charged, the cloud drops and ice crystals continue to move upward, concentrating in a diffuse layer, called the *P-region*, which can be several kilometers thick and reach the top of the cloud. The heavier, negatively charged particles are distributed somewhat vertically in the lower portion of the cloud, being concentrated in a pancake-shaped layer at an altitude of approximately 6 km. This layer, the *N-region*, is less than 1 km thick, with a horizontal span of several km. By convention, a positive dipole has been created. This hypothesis does not consider convection effects.

It is felt that in the final analysis the charge separation process will be found to involve both precipitation and convection. Gravity may not be the sole force responsible for collisions between precipitation particles and cloud drops and ice crystals. Convection probably produces the relative motion (i.e., ice particles must rise faster than graupel falls) necessary for large-scale charge separation.

Finally, laboratory experiments have demonstrated that when graupel and ice crystals collide, the polarity of the charge transferred is strongly affected by the ambient temperature, with a reversal taking place between −10 and −20°C. Below this charge-reversal temperature (i.e., at higher altitudes), collisions impart a negative charge to the graupel. Recall that observations of thunderclouds locate the main negative charge layer at an altitude of 6 km, where the temperature is approximately −15°C. For collisions below this altitude, where the temperature is higher, the graupel will become positively charged, an apparently reasonable explanation for the existence of the p-region.

Lightning

Lightning accompanies not only thunderstorms, but also volcanic eruptions, snow and dust storms, and surface nuclear detonations. However, we will deal here only with lightning produced by thunderstorms—discharges within a cloud or from cloud to cloud (intra or intercloud lightning), and from cloud to ground. When charge separation within a cloud causes local electric fields to exceed the dielectric strength of the intervening atmosphere, breakdown occurs and a lightning discharge takes place. Taking into account cloud altitude and the presence of water and ice particles, a typical value for the breakdown electric field is in the order of 1 to 2 MV/m.

Intra/Intercloud Lightning

Intracloud lightning (I-C) is generally the most frequent form of lightning, even though the opacity of clouds limits visual support of this fact. Inter-cloud lightning occurs relatively infrequently. With regard to the previously discussed global circuit, intra and intercloud lightnings represent short circuits within the generator.

Charge redistributions within the cloud (I-C lightning) initiate the storm-cell discharge process. For each discharge, a double-ended, tree-like streamer (or leader) carries positive charge from the P-region to the N-region along paths that possess the greatest concentration of charge. Each time a positively charged streamer reaches a small concentration of negative charge, a recoil streamer (*K-stroke*—nominally 1 kA peak current) returns along the ionized channel, neutralizing its positive charge. When a connection is made between highly charged regions, a high-current return stroke (e.g., 10 kA peak) takes place.

Within a few hundred milliseconds, a lightning event transforms electrostatic potential energy into electromagnetic energy (radio and light waves), heat, and acoustic energy (thunder). The streamer produces a low-light-level, continuous luminosity that is periodically intensified by a number of bright pulses of approximately 1-ms duration (attributed to the K-strokes). Radio-frequency noise, predominately in the VHF range, is generated. The high-current return stroke instantaneously raises the channel temperature to 10,000 K or higher, producing visible light and a pressure shock wave that we hear as thunder.

In 1988, it was reported[2] that maximum I-C activity and a polarity reversal of the electric field at the ground were found to be concurrent with the period of peak updraft. This takes place 5 to 10 minutes prior to the onset of intense precipitation and the strong downdrafts associated with the collapse of the updraft. These findings suggest that nature may provide a warning prior to the onset of microbursts.

The base of the N-region usually coincides with the freezing-level altitude, and thus its height varies with the temperature of the air near the ground—warmer air temperature corresponds to higher base. Since cloud-to-ground (C-G) lightning takes place predominately between the N-region and the Earth, it is less likely to occur as the cloud-base altitude increases. Global statistics show the average ratio of I-C to C-G lightning to be roughly 10:1 for the equator, 5:1 for the cooler middle latitudes (e.g., the U.S.) and 1:1 for the cold far north (e.g., Norway at 60°N). Because of this temperature dependence, a larger percentage of C-G lightning can also be expected from cold storms.

Cloud-to-Ground Lightning

Because of its visibility, much more is known about C-G lightning than I-C lightning. It most frequently lowers negative charge (electrons) to the Earth, making it part of the global circuit.

With C-G lightning, the negatively charged end of the previously mentioned double-ended tree emerges from the cloud's N-region. A faintly luminous ionized channel moves toward the Earth in a series of steps, nominally 50 m each, having a duration of 1 μsec per step with a pause of 50 μsec between steps. This channel, called the *stepped leader,* carries essentially the full potential of the N-region (e.g., −20 to −100 MV). The steps probably result from breakdowns between the high-voltage tip of the leader and small pockets of positive charge in the air. As the stepped leader approaches the Earth, at about 0.2 m/μsec, its strong electric field causes positively charged streamers to move upward from pointed, grounded objects. When the electric field between the stepped leader and one or more streamers is greater than the dielectric strength of the intervening air, breakdown takes place (see Fig. 4). Typically, this *striking distance* (so named by Franklin) is in the range of 30 to 100 m. During the leader process, the steps exhibit 1-kA peaks with an average current of ~100 A. A negative charge from 5 to 10 C (predominantly electrons), distributed along the channel, is lowered in tens of milliseconds.

With the leader-to-surface circuit now closed by this lowering of the channel's negative charge to Earth, a positive, high-current *return stroke* proceeds to neutralize the channel as it rushes up to the cloud at 100 to 300 m/μsec. The return stroke peak current produces a sudden temperature rise (e.g., 30,000 K), making the return stroke channel highly visible and causing the thunder-producing overpressure. The cloud's charge center, from which the stepped leader originated, is temporarily neutralized.

The return-stroke current, with a duration of about 1 msec, is depicted as a highly damped travelling wave, with the leader acting like an open-ended transmission line. At the moment when the current reaches the upper end of the channel, the polarity of the local field reverses (becomes positive) and is reflected. The channel's positive charge is progressively doubled until the reflected pulse reaches the

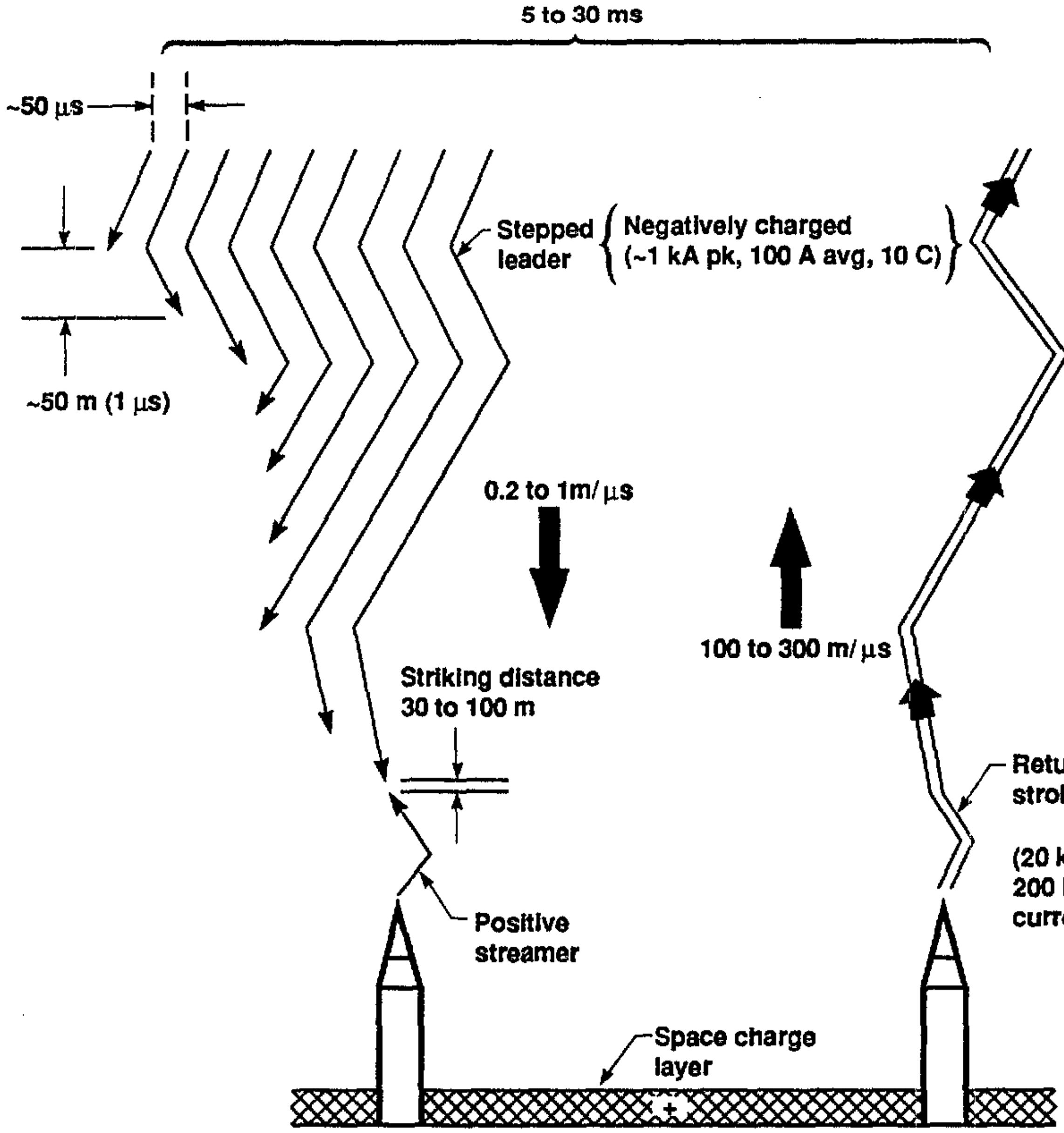


Figure 4. The development of a cloud-to-ground lightning flash. The stepped leader advances toward the ground until the striking distance (30 to 100 m) is reached. The return stroke flashes back along the ionized channel left by the stepped leader.

Earth. A junction streamer can develop, which moves upward toward a yet unneutralized negative-charge center in the cloud. Should the connection to Earth remain, a continuing or follow-on current (hundreds of amperes for hundreds of milliseconds; i.e., ≈ 10 C) will flow via the junction streamer and channel. This occurs in 25 to 50% of all C-G strokes. If, however, the current at ground level has stopped flowing, a new leader may emerge from a negative-charge center higher up. It will re-ionize the already existing channel, moving down quickly and without steps. This *dart leader* produces a subsequent return stroke. On the average, three to four return strokes occur, separated by tens of milliseconds (or tenths of a second if continuing current is present). The entire event, approximately 500 msec in duration, is referred to as a lightning *flash*. As many as 26 return strokes have been recorded for one flash. Because of the speeds involved, the human eye cannot differentiate the various portions of the lightning flash. Thus, what we perceive as flickering is actually the result of multiple return strokes.

Positive C-G strokes, in which positive charge is lowered from the P-region, occur much less frequently (10% of all C-Gs, worldwide) than negative strokes (the other 90%). *Positive lightning* can be observed near the end of a thunderstorm, or in conjunction with cold storms (in which positive C-G predominates) or severe storms that produce large hail and/or tornadoes. It emanates as a stepless leader from much higher up in the cloud (typically from the anvil) and thus has a much higher potential. The charge it lowers is in the order of 3 times that of negative lightning, meaning that the peak current will be correspondingly greater, with 200 to 300 kA being not unusual values. It rarely produces multiple strokes.

For most situations, it is the C-G return strokes that cause damage. In a subsequent section, lightning parameters will be presented in more detail, and damage mechanisms will be discussed.

Triggered Lightning

Long, man-made conductors, exposed to the high electric fields associated with a thunderstorm cloud can bring about a lightning discharge. The most common situation involves very tall towers (i.e., >100 m) from which a positive leader moves upward from the tower, resulting in a downward, negative return stroke.

In 1753, G. B. Beccaria, an Italian professor of experimental physics, demonstrated thunderstorm electrification by firing a wire-carrying rocket into the stormy sky. This method was introduced into the 20th century when M. M. Newman (1965) demonstrated the feasability of triggering C-G lightning using a rocket-borne, grounded wire fired from his research vessel. Subsequently, he sailed this floating lightning laboratory to areas of high lightning incidence, utilizing rocket-triggered lightning to test a variety of military and civilian aerospace components and systems. Land-based, rocket-triggered lightning has been conducted by French government scientists since 1973. In 1979, the French began collaborating with American scientists in conducting rocket-triggered lightning experiments both in the mountains of New Mexico and the coastal flatlands of NASA's Kennedy Space Center (KSC) in Florida. The Japanese have also experimented with rocket-triggered lightning at a sea-level site in central Japan. The KSC area has one of the highest annual frequencies of thunderstorm and lightning activity in the U.S. Since the time and location of a C-G lightning flash are unpredictable, the importance of rocket triggering is that lightning can be repeatedly directed to a specific target within a known time period. Its characteristics are acceptably close to those of natural C-G lightning, making it possible to study the direct and induced effects of lightning on protected and unprotected systems, as well as investigate the charateristics of lightning channels.

The mechanism of triggering lightning can be explained as follows. When a conductor is located in a uniform electric field such that it is normal to the field's equipotential planes, the field is enhanced in proportion to the length of the conductor; e.g., a 50-m-long conductor may cause an enhancement of 50 times or more. If located in a 50-kV/m field, the upper end of the conductor would experience an enhanced field of 2.5 MV/m, a value greater than that required to break down air. If the top of the conductor has a tip with a relatively small radius of curvature, corona discharge will occur, significantly reducing the field at the tip and lowering, but not eliminating, the probability of its triggering lightning. However, if the conductor moves through the field with sufficient velocity (e.g., a rocket during launch or an aircraft in flight), corona will not have time to develop, and a triggered flash is more likely.

The exhaust plume of a rising rocket is also conductive. Both Apollo 12 (the second manned lunar mission—Nov. '69) and Atlas-Centaur 67 (AC-67—an unmanned launch vehicle—Mar. '87) were launched in the presence of high-amplitude electric fields and subsequently affected by self-triggered lightning. Apollo 12 triggered a C-G discharge at about 2 km and an I-C discharge at about 4.5 km. Nine sensors and associated solid-state signal conditioners permanently failed. Systems upsets included three fuel cells that were disconnected from their busses, disturbed clock and timing signals, activation of numerous alarms and warning indicators, loss of the inertial navigation's attitude references, and loss of communications. The mission's survival was attributed to weak flashes and the ability of the crew to reset the computers. In the case of AC-67, when the vehicle was at about 3.5 km, four C-G strokes were observed below it. This caused an upset to the onboard digital computer, which then issued an erroneous yaw command to the engine that caused excessive dynamic loading and the subsequent breakup of the vehicle and the loss of its $160-million payload (the most expensive rocket-triggered lightning "experiment" yet conducted).

Statistics indicate that a commercial aircraft can expect to be struck by lightning about once every 3000 flight-hours. Damage can range from minor (a small amount of pitting of the metallic skin or upset of a noncritical electrical system) to moderate (destruction of the radome) to catastropic (a fuel-tank explosion or failure of a critical electronics system and subsequent crash). In rare instances, an aircraft just happens to intersect a lightning channel. Generally, they trigger their own lightning while ascending or descending through clouds in precipitation and turbulence at the freezing-level altitude. Military aircraft are struck once every 30 to 40,000 flight-hours because of their significantly different flight profiles. Exceptions to this are antisubmarine warfare planes, which are the most frequently struck of all aircraft because of the extended periods of time they spend in level flight at relatively low altitudes.

Lightning Characteristics

By now it should be obvious that the study of atmospheric electrification involves a wide range of topics and disciplines. Fortunately, since our principal interest relates to warning and protection, only a few parameters must be considered. Although I-C lightning will be discussed, C-G lightning presents the most serious threat and will receive the most attention. Lightning is an unpredictable transient phenomenon with characteristics that vary widely from flash to flash and are difficult to measure.

Keep in mind that values presented for the various parameters are averages based on data collected at a number of geographical locations, by a variety of scientists, and over many years. Also, one should recognize that the kind of lightning data that is important depends on whether one is interested in atmospheric science, meteorology, personnel safety, or systems protection.

Frequency of Occurrence

While it is impossible to predict exactly when and where lightning will strike, statistical information gathered over the years can provide some indication of the most likely thunderstorm locations, seasons, and times of day. A commonly used method for presenting lightning-occurrence data is the *isokeraunic map* (see Fig. 5). Contour lines depict the number of *thunderstorm days* per month or year that a particular region can expect to experience. These maps are based on weather-bureau records over an extended period (e.g., 30 years). A thunderstorm day is defined as any day a trained observer hears thunder at least once—whether it is from an I-C or C-G discharge. These maps are regularly referred to by engineers who must provide risk analyses for major systems that are vulnerable to lightning (e.g., nuclear power plants, power transmission lines, communications facilities, etc.). However, the isokeraunic levels are a poor indicator of lightning activity. One thunderstorm day will be noted if a single thunderclap or 1000 are heard on that day. In addition, recent studies indicate that thunder was not heard for 22 to 40% of lightning flashes detected by other means. Although the probability of lightning striking a particular area can be easily calculated, the procedure utilizes statistically determined values that include isokeraunic levels. Obviously, such calculations should be viewed with a great deal of caution.

Despite the caveats associated with isokeraunic levels, they are somewhat useful in providing a rough idea of the relative incidence of lightning in a particular region. A general rule of thumb, based on a large amount of worldwide data, estimates the Earth-*flash density* to be 1 to 2 C-G flashes per 10 thunderstorm days per km^2. New techniques are now in use for detecting C-G flashes and archiving the data. This should lead to more realistic lightning risk assessments being possible in the future.

I-C Lightning

During the period of initial breakdown within a cloud, current levels are small and path lengths are short, resulting in the generation of radio noise predominantly in the VHF spectrum. When a high-current discharge takes place, a peak current of 10 kA can flow through a channel of 1 km or more, producing a strong lightning electromagnetic pulse (LEMP) with a spectral density centered at about 4.5 kHz. The

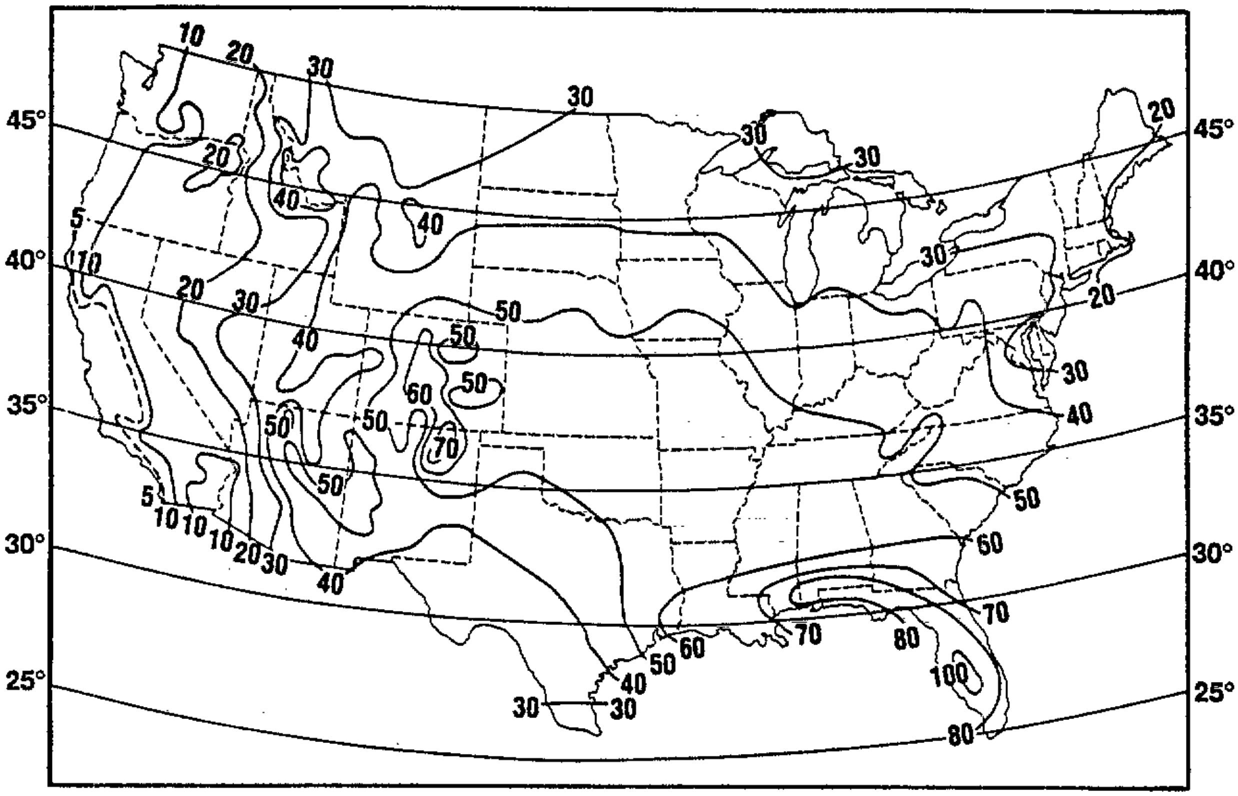


Figure 5. Example of an isokeraunic map, showing the average number of thunderstorm days/yr.

channel can have a significant horizontal component, thus coupling energy into horizontal conductors; e.g., power and communication cables located at or near the surface or an aircraft in flight. As previously mentioned, the discharge is also accompanied by a light pulse and thunder.

C-G Lightning

Return-stroke current is a very important parameter. Besides being responsible for lightning-related damage and injury, we will see later that it also provides a degree of early warning. Scientists in the not-too-distant past believed that lightning was oscillatory in nature, an idea that possibly originated because of the flickering observed with multiple-return-stroke flashes. Today its unidirectional nature is universally accepted.

Negative lightning, being the most common type, will be covered first. As a stepped leader approaches the Earth, the high potential at its tip produces increasingly strong electric fields at the Earth's surface. *Streamers* of positive ions flow into the air from grounded pointed objects such as pine needles, blades of grass, towers, and raised golf clubs. These *point-discharge currents,* on the order of tens to hundreds of microamperes flow until the distance to the stepped leader is small enough to cause them to become concentrated into a few streamers. When the streamer-to-leader distance becomes less than the striking distance, closure of the cloud-Earth circuit takes place, allowing positive charge to move upward, neutralizing the negative leader channel. A high-current return stroke now flows from the Earth, through the grounded object whose streamer was "chosen," at a location referred to as the *lightning attachment point.* How this return stroke causes damage will be discussed in a later section.

The magnitude and duration of a return stroke was first evaluated in the late 1800s. By studying a conductor that had been fused by lightning, an estimate was made by determining the current that would have been required to fuse the conductor. Subsequent methods compared the fusing, crushing, and pitting of struck conductors with laboratory results. In 1897, F. Pockels discovered that a basalt rock struck by lightning exhibited residual magnetism that was proportional to the peak magnetizing field intensity. In 1932, C. M. Foust and H. P. Kuehni produced the *magnetic link*, a lightning-current sensor commonly used today, by bundling high-retentivity steel strips together.

Most of the lightning-current data available today has come from magnetic-link measurements on high-voltage transmission lines and tall towers. Measurements made using high-speed oscillographs showed the return stroke to be unidirectional and provided information about its waveshape. The return stroke is a current pulse that rises to its peak value in a short time, falls off more slowly, and exhibits a relatively long continuing, or follow-on, current (see Fig. 6). It is represented by the following equation:

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t}) + I_1(e^{-\gamma t}) \quad , \tag{1}$$

where the first term is the *double-exponential* pulse, and the second is the *follow-on current*.

Positive lightning, as previously mentioned, generally occurs at the end of a storm or in conjunction with a cold storm. Now that lightning-detection instrumentation is capable of determining the polarity of flashes, more positive lightning is being observed, particularly in conjunction with cold or severe storms. While the probability of being struck by a positive flash is lower than for a negative one, the consequences could be worse. The current rise rate is much slower than for negative lightning, but the average and maximum values of peak currents and *action integrals** are significantly higher.

*** The Action Integral**

The total energy contained in a lightning stroke can be expressed as

$$W = \int_0^t P\,dt = \int_0^t I^2 R\,dt = R\int_0^t I^2 dt \ . \tag{2}$$

where W = energy in joules, P = power in watts, t = stroke duration in seconds, I = current in amperes, and R = resistance in ohms.

One can see that the energy dissipated is very dependent on the value of R. If lightning strikes a metal flagpole (low R), little damage is done. If it strikes a tree (high R), the damage can be spectacular. To quantify the energy input when the resistance is not known, Eq. (2) is divided by R, yielding

$$\frac{W}{R} = \int_0^t I^2\,dt = I_{pk}^2 t_d \ , \tag{3}$$

which is referred to as the energy input, or action integral, with the units of A^2·sec. The lightning-stroke duration, t_d, is defined as the time interval during which the current amplitude is greater than 50% of its peak value, I_{pk}.

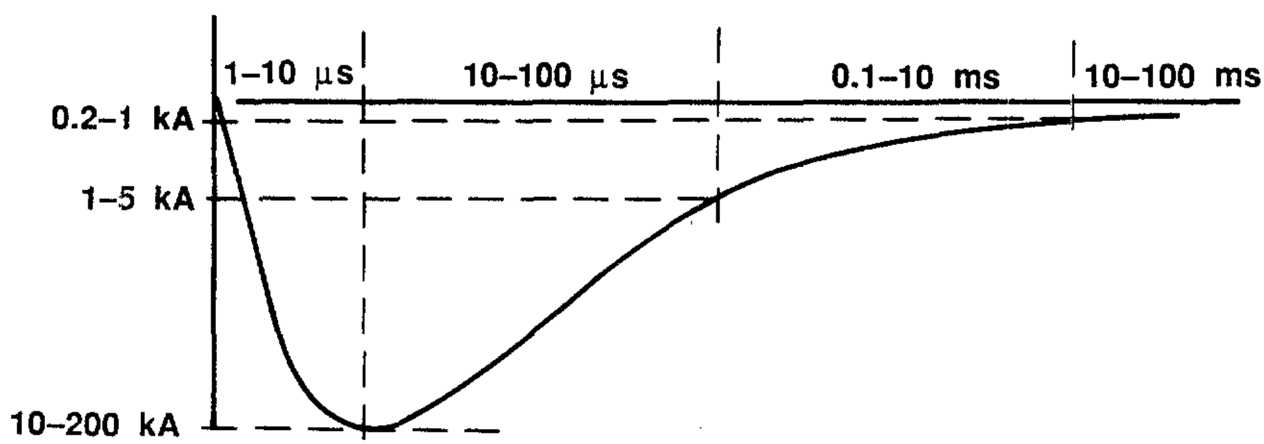


Figure 6. While naturally occurring lightning exhibits a wide variety of waveshapes, the waveform of the return stroke's current is approximated by a double exponential with a high rate of rise, a significantly lower rate of decay, and an extended continuing, or follow-on, current.

The following set of lightning statistics comes from the large volume of available lightning data:

For negative lightning:

Peak Current—max.	-200 kA (1st-percentile value)
Peak Current—median	- 20 kA (50th-percentile value)
Rise time to current peak	10 μsec
Fall time to 50% of peak	50 μsec
Current rise rate—max.	200 kA/μsec
Current rise rate—median	40 kA/μsec
Action integral—max.	1.5×10^6 $A^2 \cdot sec$
Action integral—median	6.5×10^4 $A^2 \cdot sec$
Return strokes per flash	4.6

For positive lightning (for which less data is available):

Peak Current—max.	250 to 500 kA
Peak Current—median	35 kA
Rise time to current peak	20 to 50 μsec
Fall time to 50% of peak	200 to 2000 μsec
Current rise rate—max.	<20 kA/μsec
Current rise rate—median	2.4 kA/μsec
Action integral—max.	2×10^7 $A^2 \cdot sec$
Action integral—median	6.5×10^5 $A^2 \cdot sec$
Return strokes per flash	1

As with I-C lightning, the radio noise generated by the return C-G stroke is a low-frequency phenomenon whose spectral density is centered at 4.5 kHz and diminishes to near zero beyond 100 kHz.

To ensure personnel safety and optimize resource protection, a combination of timely and credible warnings plus suitable protective methods are required.

Lightning Threat Warning

Lightning, although unpredictable, does announce itself in a variety of ways. A thunderstorm, while still in the distance, does not represent an immediate local threat. The C-G lightning it produces does provide some advance warning if it's visible, audible, and/or electromagnetic signals are detected. However, the unanticipated first C-G flash from a summertime convective storm or a frontal storm that has not started producing lightning can come as an unpleasant and dangerous surprise.

Effective lightning-threat warning depends on designated "responsible individuals" being alerted to a developing threat, and making the appropriate decisions (e.g., continue/stop/resume the activity). These decisions will be based on personal weather observations, experience, and common sense, augmented with as much of the following information as is available: weather forecasts, cloud-electrification warning, detection of electrical-discharge activity, and C-G lightning location and tracking.

It is important that these people be alerted soon enough to permit the appropriate action to be taken. However, since they will probably have other responsibilities, the alert should come only when a legitimate threat exists. It is equally important that the end of the threat be properly recognized so that the endangered activity (e.g., work) is neither curtailed for an unnecessarily long period of time nor resumed while a danger still exists.

Cloud-Electrification Warning

As discussed earlier, the global circuit produces a fair-weather electric field, at the surface, of approximately −100 V/m (+100 V/m if referring to potential gradient rather than electric field). When charged clouds move into an area or develop overhead, the much higher potentials of their charge centers and their proximity to the Earth cause the local electric field to depart significantly from the fair-weather value. As the magnitude of the electric field increases, there is generally a point in time when the polarity reverses. Whenever a lightning discharge occurs, the associated cloud charge center is neutralized instantaneously, followed by a gradual recharging (30 sec to 1 min, typically). The electric field generally follows these transitions.

Several types of instruments, located at or near ground level, are commonly used to monitor atmospheric electrification. The magnitude and polarity of the dc electric field at the Earth's surface can be measured with an instrument known as an *electric field mill* (EFM). The EFM employs a fixed electrode (stator), often consisting of several segments, connected to ground via a sensitive current-measuring circuit. The stator is alternately exposed to and shielded from the atmospheric electric field by means of a rotating, grounded, conductive plate (rotor). During exposure intervals, a charge is induced in the stator by the electric field. During shielding intervals, the charge drains off to the Earth via the current measuring circuit. This process generates an alternating voltage proportional to the electric field.

It is important to realize that when the measured field departs from the fair-weather value (e.g., doubles in magnitude or reverses in polarity), dangerous clouds are relatively close (e.g., 8 to 12 km away).

Although fairly widely used, EFMs have several shortcomings. Ideally, the stator should be located exactly at ground level. However, this places the rotor in a position where it can be damaged by, and do damage to, wildlife and people. Also, it can be buried by dirt and snow or submerged by heavy rain. Raising it above ground level solves that problem but introduces another. When a charged body is located above a large, flat, conductive ground plane, the electric field lines are normal to the plane, with uniformly spaced equipotential planes parallel to the ground plane. A local discontinuity in the ground plane, such as an upward protrusion, will compress the equipotential planes, thus enhancing the field strength around the protrusion and thereby increasing the apparent magnitude of the measured electric field. Elevating the EFM above the Earth's surface produces such an *enhancement*. This can be compensated for by reducing the gain of the signal-conditioning amplifier in accordance with the manufacturer's recommendations.

Tall, grounded structures such as buildings, towers, light poles, and security fences also produce discontinuities of a different kind. If an EFM is located close to one of these structures, it is partially shielded from the actual field and will indicate a much lower value. This problem can be overcome by careful placement of the EFM. Recommended practice is to separate an EFM from a structure by a distance equal to at least twice the structure's height.

The phenomenon of *space charge* presents a much more serious problem. When the magnitude of the electric field exceeds about 2 kV/m, grounded, elevated, pointed objects on the surface (e.g., trees, bushes, and man-made structures) go into *corona point discharge*, producing a layer of monopolar ions (space charge) with a polarity opposite to that of the cloud charge causing the corona. This space charge, generally concentrated within several tens of meters above the Earth's surface, affects only the electric fields between itself and the surface. An unpredictable variable, it creates an electric field that masks a surface-mounted EFM from the true magnitude of the cloud's electric field and also makes it impossible to accurately correct the enhancement effect associated with an elevated EFM. Even if an EFM's immediate environment is free from corona-producing pointed objects, surface winds can blow space charge in from nearby areas. The relatively low mobility of the ions allows the space charge to persist for five minutes or longer after the cloud-produced field that caused it has changed in magnitude and/or polarity.

Finally, the motor-driven rotor is subject to damage and requires periodic maintenance; and particulate buildup on either the rotor or stator will affect the calibration.

A second method of measuring atmospheric electrification is to use a probe containing a low-level *radioactive source*, generally polonium, and a voltmeter with a very high input resistance (e.g., 10^{12} Ω). Ions produced by the source bring the probe to the atmospheric potential existing at the measurement point. The potential difference measured indicates the average electric field between the probe and the ground. This method suffers from the usual difficulties associated with achieving and maintaining a very high resistance.

A third method measures corona current by placing a sharpened metal rod in the presence of a high electric field. Unlike EFMs or radioactive probes, conventional *corona-current sensors* do not work in electric fields much below 3 kV/m. This makes them useless as pre-first-flash warning instruments because a field of ± 1 kV/m is generally the level for sounding an alert, and ± 2 kV/m is a typical alarm level. Also, their readings are adversely affected by the wind.

These problems have been overcome by a new, innovative, active corona-current sensor, prototypes of which were successfully demonstrated at NASA's KSC during the summer of 1988. This relatively simple, proprietary sensor has no moving parts. Being mounted above a significant portion of the space-charge layer, it is not as affected by space-charge and enhancement problems as are EFMs located at or above ground level. It measures the magnitude and polarity of the atmospheric electric potential by means of a very sharp, elevated, corona point probe (e.g., 20 m above the ground at KSC), energized to a voltage of several kilovolts ac through a resistance/capacitance network. A continuous corona current discharges into the air as a result of the sharp point, the ambient electric field, and the excitation voltage. The resistance of the ion cloud surrounding the point varies significantly with wind velocity. However, since the sensor's fixed resistance is much greater than the resistance of the ion cloud, most of the *IR* drop is across the sensor's resistance, making the corona current basically insensitive to wind. For this reason, the sensor is capable of measuring small fields, including those existing in clear weather.

The electric field (in volts/meter) is directly proportional to the product of the corona current and the sensor resistance (i.e., the atmospheric potential at the probe) divided by the height (in meters) of the probe tip. This operation, performed by the sensor's electronics, provides an analog signal proportional to the electric field.

The real concerns with a storm cloud are (1) is it electrically charged, and (2) what is the magnitude of its potential? The presence of space charge affects readings from all types of sensors located on or relatively near the surface. However, in recent studies that used a combination of ground-level EFMs collocated with an elevated, active, corona-current sensor, the space charge was easily determined. It is believed that, by combining this data with the time history of the space charge, an algorithm can be developed for determining the cloud's electric field.[3]

Detection of Electrical-Discharge Activity

If a suspicious storm cloud is off in the distance, it is not possible to determine that the cloud is electrically active and that it represents a possible threat unless electrical discharge is detected. How much warning time is there before the first C-G flash occurs? From statistical data, we know that cloud icing and electrification commence within 5 to 10 min after onset of the strong updraft and coincident with the first weather-radar echos from aloft; the first discharge, almost always I-C, takes place in another 5 to 10 min; and the first C-G flash occurs 15 to 20 min after the initial radar echo.[4] Thus, the warning time for the distant storm depends on how far away it is and what types of observations are being made. Even if we know the distance to a storm cell and its velocity (i.e., the mean wind velocity), we still cannot predict when and where lightning will strike because C-G strikes exhibit a "random-walk" pattern with an average step of approximately 3 km from flash to flash.

If a convective storm develops overhead and radar data is available, the warning time may be 15 min, although this type of storm has been known to go from a clear sky to the first flash in 10 to 12 min. If the initial I-C discharge is the first observation, a C-G flash can be expected in 10 min or less, even immediately sometimes. Although 1 hr is the typical duration of a convective storm, a rapidly developed storm dissipates quickly, and a slowly developed storm dissipates slowly.

Either visual or electro-optical observation can be used to detect both I-C and C-G discharges. Unless a light pulse is obscured or diffused by dark clouds, a single observer should be able to provide such information as bearing to the pulse, approximate range, and time of occurrence. Also, the high peak temperature of the return-stroke channel causes an audible pressure pulse (*thunder*) on the order of 10 to 30 atmospheres with a peak spectral amplitude at 100 Hz. Thunder can be heard approximately 25 km from an I-C discharge and 5 km from a C-G flash, depending on such factors as the intensity of the discharge, wind direction, and terrain. Both the light pulse and thunder are positive indicators of an active electrical storm.

In addition to light pulses, cloud discharges produce electromagnetic radiation known as *atmospherics* or *spherics* over a fairly wide range of frequencies. Because of their short path lengths, initial breakdowns and stepped leaders radiate predominantly in the VHF portion of the rf spectrum and, with a suitable receiver, it is possible to detect these precursors to C-G lightning activity. The radiation from a typical C-G return stroke is equivalent to that of a 20-MW spark-gap transmitter, with a signal that predominates well below 1 MHz. Since the electrostatic field intensity component of this radiation varies inversely as the cube of the distance (the *$1/D^3$ rule*), the strength of the received signal provides some indication of the distance to the flash.

A simple AM-radio receiver, tuned to the low end of the broadcast band (550 kHz), can be used as a rudimentary spherics or C-G flash detector. If weak, periodic, static impulses are heard, a storm cell has started producing C-G lightning. Increasing amplitude indicates that either the storm is approaching (i.e., a frontal storm) or that larger-amplitude strokes are taking place. An increase in the number of static "crashes" per minute (the flash rate) means that the storm is growing in intensity. When a frontal storm reaches peak activity, the lightning-produced signals will occur at essentially regular intervals.

A somewhat more sophisticated *flash-warning instrument* consists of a filter tuned to the lightning stroke's low-frequency spectrum and an amplifier. Since the received signal strength of an average-amplitude (20-kA) C-G flash can be estimated by the $1/D^3$ rule (where D is the distance from flash to receiver), the gain of the amplifier can be set to provide a specific output signal corresponding to a particular distance. Unfortunately, lightning is far from being a constant source—studies have shown that strokes occurring at a given fixed distance produce field intensities that can vary by as much as a factor of 100. Thus, it is not possible to accurately determine the distance to a single stroke. (Note: recent experiments performed using a flat-plate electric-field antenna in conjunction with appropriate algorithms show promise in overcoming this problem.) However, statistics come to the rescue. By the use of several amplifiers with gains corresponding to different flash distances (i.e., highest gain for farthest and lowest gain for closest), the signals can be quantized. The mean storm distance corresponds to the range showing the highest number of strokes.

A recently developed *electro-optical sensor* is capable of detecting lightning pulses not visible to the eye; e.g., distant I-C lightning under daylight conditions. Since I-C generally precedes C-G lightning by 10 to 15 min, this sensor can be used for pre-first-flash warning. When this small, lightweight, handheld instrument is pointed at a suspicious cloud, its first audible "beep" (an electrical output pulse is also produced) warns the operator that the cloud is beginning to produce lightning. These sensors also can be used in an unattended, surveillance mode by mounting them and connecting their electrical outputs to a suitable alarm system. The acceptance angle of the detectors' lenses would be selected to provide the desired coverage.

In 1987, the French government announced the *SAFIR* lightning early warning system, which is now in use at their rocket launch facilities and is expected to be installed at KSC. SAFIR uses three receiver sites, located several kilometers apart. Each site has an array of VHF antennas and uses interferometry techniques to detect and locate the high-altitude electrical-discharge precursors to lightning, as well as I-C and C-G lightning.

Location and Tracking of C-G Lightning

In the simplest form of lightning locating, a lone observer determines the bearing of a single visible C-G flash, counts the number of seconds between the lightning and the thunderclap, and divides by 3 to obtain the approximate distance in kilometers (or by 5 to obtain miles—velocity of sound is approximately 1/3 km/sec or 1/5 mi/sec). If the *flash-bang* interval is 3 sec or less, the storm is essentially overhead! This flash-bang technique has been made more suitable for scientific research by combining a light-sensitive sensor, a microphone, and an intervalometer. By using several widely separated observers or sensors, it is possible to obtain several bearings and locate the strike point by triangulation. This technique has some obvious shortcomings.

In two significantly more sophisticated methods, the strong electromagnetic signals radiated by C-G lightning are detected at several distant locations and, by computer data processing, a large number of flashes over a wide area can be located and tracked. Since such data can be archived, subsequent analysis can provide valuable statistical information regarding thunderstorm frequency and history, etc.

In one method, *magnetic direction finding* (MDF), a pair of vertically polarized, crossed-loop antennas receive the magnetic component of the C-G radiation, resolving it into sine and cosine voltages, thus providing one *line of position* (*LOP*) per receiver site. Two or more suitably located antenna sites provide intersecting LOPs that locate the C-G flash by triangulation. At each site, a companion electric-field antenna provides a signal that is analyzed to verify that a lightning pulse has been received. All necessary information from each receiver site is transmitted to a central location where data analysis is performed. Flash locations are recorded and displayed on an area map, along with flash polarity and magnitude information. This technique requires precise alignment of the loop antennas and a good antenna-grounding system. Since it senses the magnetic component, it is sensitive to magnetic anomolies near the antenna, which cause a problem referred to as *site error*. Where site errors are fixed, computer analysis of a large number of random flashes can provide correction factors to minimize location errors. It is much more difficult to correct for unexpected or variable magnetic effects, such as a large piece of mobile equipment or new construction near an antenna or a large horizontal component in the return-stroke channel. A state university is currently acquiring and processing lightning location data from a number of individual, mostly government-owned, MDF systems located around the country. This project is evaluating the feasibility of a nationwide lightning tracking network. At present, only government and research organizations are being offered access to data from this network.

In the *time-of-arrival* (TOA) method, electromagnetic signals from C-G flashes are received with single, vertical, whip antennas at several receiver sites. As with the MDF system, the signal must be analyzed to verify that it is C-G lightning. Each valid signal is time-tagged, and all the data is transmitted to a central computer for processing. With TOA, two sites are required to compute a single hyperbolic LOP for each stroke. The intersection of two or more hyperbolas locates a stroke, which is then displayed on a map. Polarity and magnitude data are also provided. To make this technique work, a very accurate time signal (such as is available from loran stations, satellites, and TV stations) must be available at all receiver sites. The antenna should not be situated where it is shielded by large metallic structures, but it does not have any special alignment requirements, and it is not affected by magnetic anomalies. Also, a nationwide, lightning-detection network has been established, which routes lightning-stroke data from a number of regional TOA systems to a supercomputer center, where it is processed and then sent to an Earth station for transmission to a geosynchronous satellite. Lightning-stroke information is then made available to commercial subscribers via satellite downlinks.

When a distant storm is producing C-G lightning, both the MDF and the TOA systems are capable of locating and tracking it, providing a reasonable warning. However, they are of no use in situations where cloud electrification exists but no C-G flashes have occurred.

References

1. Hans Volland, *Atmospheric Electrodynamics* (Springer-Verlag, New York, 1984).
2. Earle R. Williams, "The Electrification of Thunderstorms," *Sci. Am.* 259(5), 88 (1988).
3. R. J. Markson, private communication, Airborne Research Associates, Inc., Weston, MA (1989).
4. Steven J. Goodman, Dennis E. Buechler, Patrick D. Wright, W. David Rust, and Kurt E. Nielsen, "Polarization Radar and Electrical Observations of Micro-burst Producing Storms During COHMEX," *Proc. 24th Conf. Radar Meteorology,* 27-31 March 1989, Tallahassee, FL (in press).

Bibliography

J. Alan Chalmers, *Atmospheric Electricity,* 2nd ed. (Pergamon Press, New York, 1987).

R. H. Golde (ed.), *Lightning,* vol. 1, "Physics of Lightning," (Academic Press, New York, 1977).

Steven J. Goodman, Dennis E. Buechler, and Paul J. Meyer, "Convective Tendency Images Derived from a Combination of Lightning and Satellite Data," *Weather and Forecasting,* 3(3), (Am. Meteorological Soc., 1988).

William C. Hart and Edgar W. Malone, *Lightning and Lightning Protection* (Don White Consultants, Inc., Gainesville, VA, 1984).

Richard T. Hasbrouck, *Lightning -- Understanding It and Protecting Systems From Its Effects,* Lawrence Livermore National Laboratory, Livermore, CA., UCRL-53925 (1989).

Martin A. Uman, *Lightning* (McGraw-Hill, New York, 1969).

Martin A. Uman, "Natural and Artificially-Initiated Lightning and Lightning Test Standards," *Proc. IEEE* 76(12), 1548 (1988).

Martin A. Uman, *Understanding Lightning* (Bek Technical Publications, Inc., Carnegie, PA 1971).

Index

DIMENSIONS

SAFIR
PRINCIPLES OF A SYSTEM FOR MONITORING THUNDERSTORM ACTIVITY AND WARNING AGAINST LIGHTNING

FUNCTIONS AND FEATURES

The SAFIR system has been developed by the French National Agency for Aerospace Research (ONERA). It is now being used by CNES at the Kourou Space Center and by the French Department of Defense (Délégation Générale pour l'Armement) at the Landes Test Center.

SAFIR is the only real-time, wide coverage system to allow early detection and localization of thunderstorm phenomena before any lightning strikes the ground. The system locates and scans the electrical activity of thunderstorm clouds and provides the user with a map of ground and air lightning stroke hazard; for high-risk areas, it automatically computes and transmits warning information.

When storm cells form, the typical early warning time delay is 15 minutes before the first ground strokes occur. For a propagating storm front, this may reach several hours.

Such an early warning capability is ensured by electromagnetically detecting electrical discharges which occur within a storm cloud as it builds-up and grows; these discharges are a precursor phenomenon allowing a storm cloud to be identified and located up to 30 minutes in advance, and its path to be predicted. These internally occuring events are also an indication of thunderstorm severity and provide potential means for detecting the most devastating phenomena due to thunderstorms (strong rainfalls, hail, turbulences, wind shears) and give an early warning.

Owing to its early warning and real time high-risk zones mapping capabilities, SAFIR offers a decision aid and safety means in several areas: aviation, industry, defense, power and communications networks, space.

The information derived by the system is systematically stored. It is also used to carry out a later analysis of thunderstorm situations, and to make statistical maps of lightning hazards.

TYPICAL SYSTEM SET UP

SAFIR is typically made-up of three detection stations spaced about 100 kms apart and of a central station. The latter collects data transmitted by the detection stations, carries-out appropriate processing and displays position and warning data on a high-resolution graphical display.

The user interface was specially optimized in order to allow an immediate interpretation of warning information, and to provide efficient decision aid.

The central station controls a server system for broadcasting SAFIR data, whether automatically or on request, to many other users through the telephone network.

The geographical arrangement of stations is optimized in order to best suit the coverage and accuracy requirements. The minimum coverage of the system is 300 x 300 kms, with a typical localization accuracy of 2 kms.

Operation is fully automatic, with tests performed periodically on all units and the system's operational status continuously summarized on the central station's control display. This status may be automatically transmitted to DIMENSIONS' technical center.

The system is designed for minimum maintenance.

WARNING INFORMATIONS AND HOW IT IS DISTRIBUTED

The overall thunderstorm activity monitoring and warning data are available in real time at the central station. Users may access:

- **location of lightning strokes**,
- **real-time cartography of hazardous areas** both on ground and in the air,
- **short term predicted mapping of hazardous areas** (from 10 mins to more than an hour),
- **automatic warning** for user-defined sensitive areas.

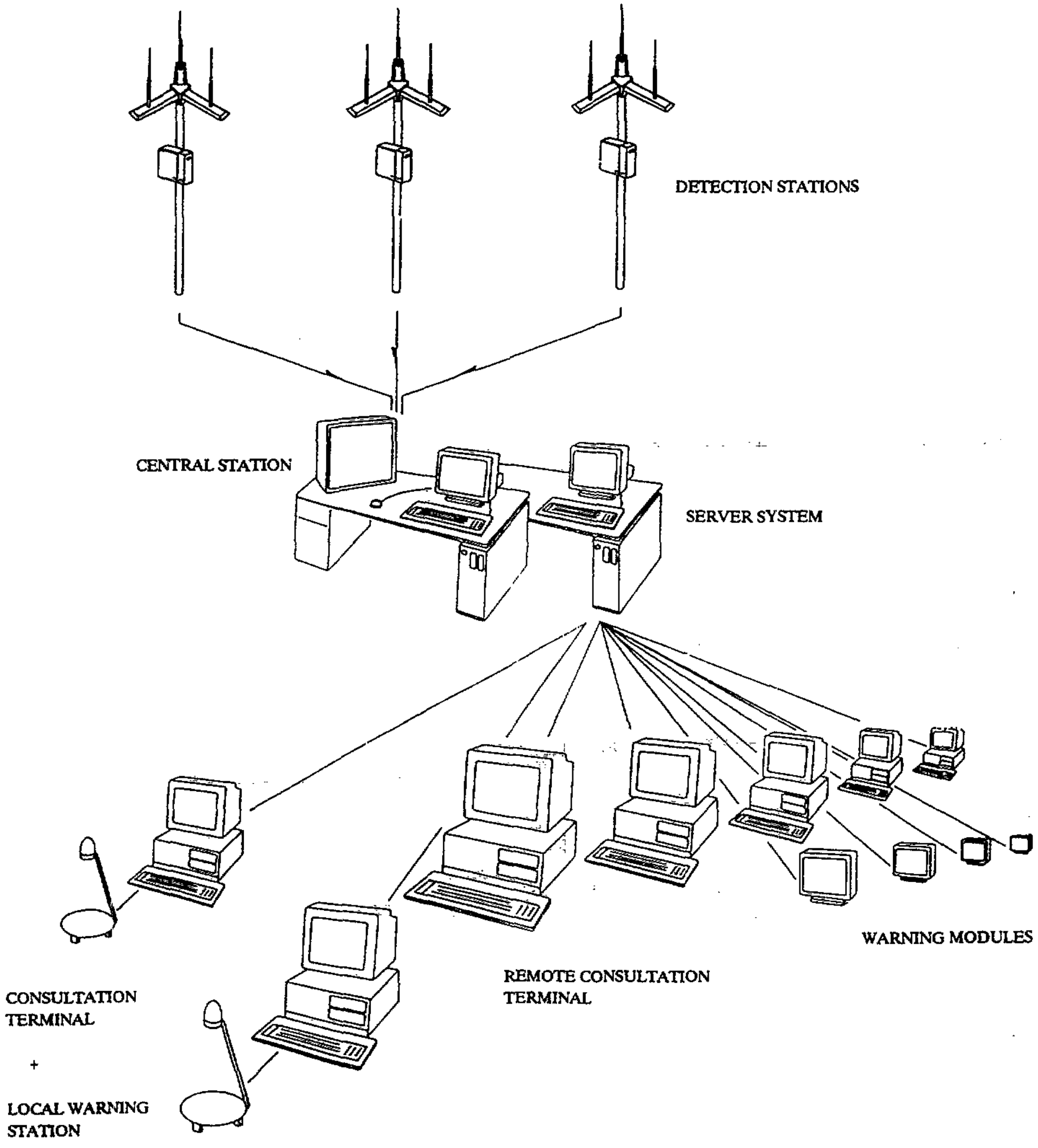
These informations are visualized at the central station on a high resolution graphic display and are easily accessed through menus. there can also be send on real time to all users through the telephone network.

To that end, the central station is provided with a server system which manages incoming calls and distribution of information to the various user terminals. The latter are of two different types:

Warning module: the user has a unit which displays warning level and delay; it is automatically called and started by the SAFIR server when the system predicts lightning hazard for the user's site. This unit may be installed indoors as well as outdoors.

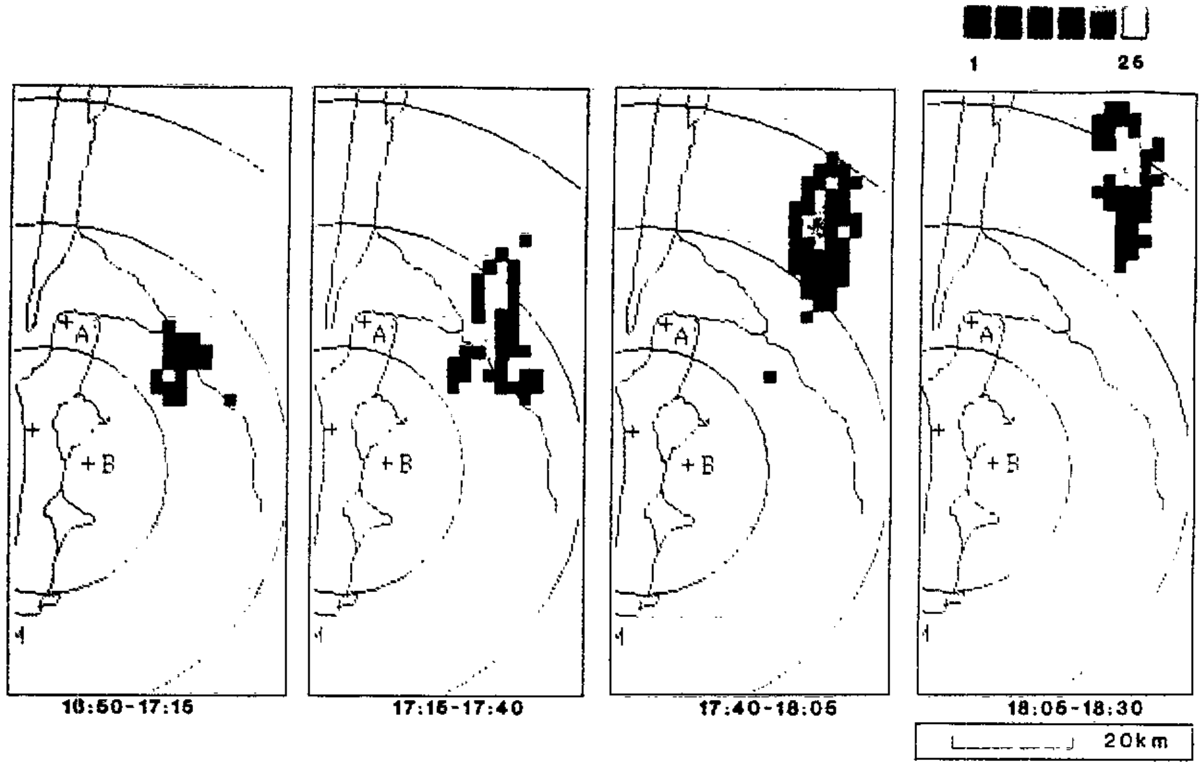
Consultation terminal: the user is provided with a micro-computer running a software which allows him to retrieve all of the mapping data pertaining to the dangerous areas. This unit may also be called automatically by the server system in case of predictible hazard. A local lightning warning station can be connected to the consultation terminal. It will detect the electric field occuring in the vicinity of a thunderstorm cloud (< 5 kms) when it forms, and allow, in the special case where the storm builds-up close to the user's site, the warning notification delay to be improved by about 10 mins.

The server system also constructs a data base which keeps track of all thunderstorm situations. It may be accessed in order to trace back, in delayed time, a storm event, or to derive lightning stroke statistics.

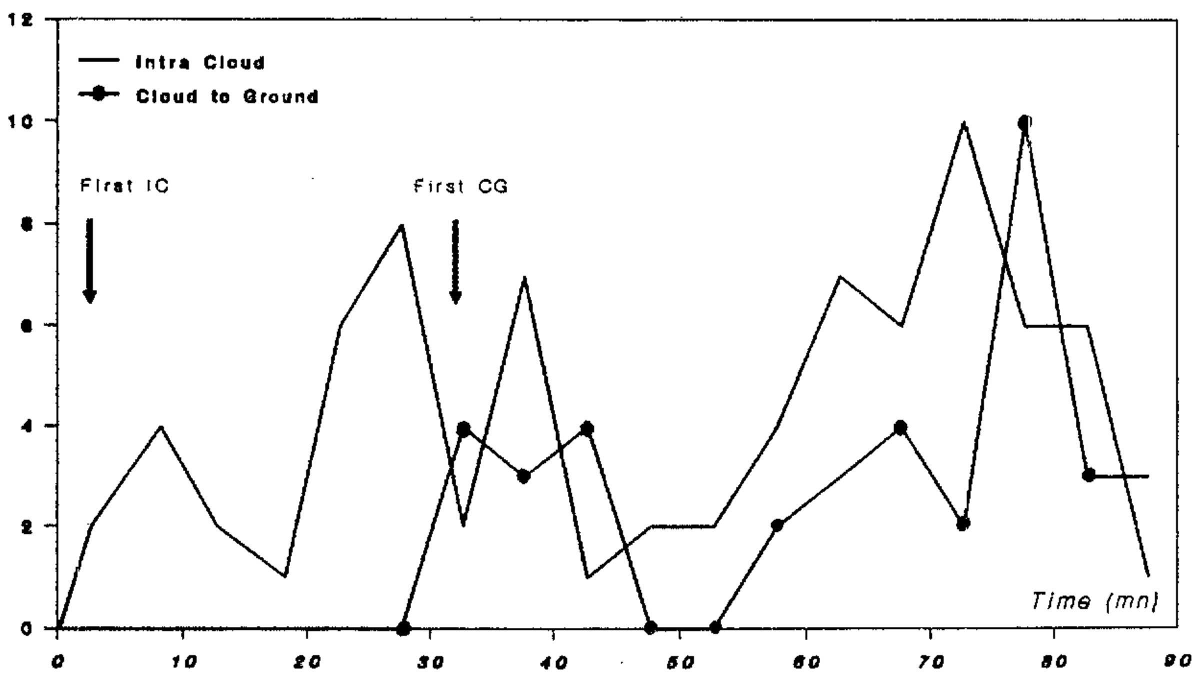


CONFIGURATION OF THE SAFIR SYSTEM AND ITS WARNING INFORMATION DISTRIBUTION NETWORK

A



B



Example of thunderstorm activity as visualized with the SAFIR system. This example illustrates the early warning performances of the system.

A: time sequence of lightning activity maps

B: evolutions with time of the numbers of intra-cloud and cloud-to-ground flashes per 5mn periods

Comments:

- First cloud to ground flashes are produced 27 minutes after the first intra-cloud flash
- Peaks in cloud-to-ground activity are systematically observed after peaks in intra-cloud activity

NATURAL LIGHTNING HAZARDS

Short Course

Dallas/Fort Worth, 19-20 July 1988

Presenter: Robert Olsen, ASL

FEBRUARY 26, 1990

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  K. Mielke, National Weather Service, Western Region
- Severe Weather Forecasting

  A. Edman, National Severe Weather Center
- Pulling It All Together: Atlas/Centaur 67, A Case Study

  Dr. H. Christian, NASA/Marshal

FEBRUARY 26, 1990

NATIONAL LIGHTNING HAZARDS

Short Course -- 5 Tapes

Available upon Letter Request:

Dr. John Theon
NASA Headquarters
Code EE
Washington, DC 20546

FEBRUARY 26, 1990

Dear Colleague:

Lightning constitutes a serious threat to all aerospace craft which must fly in or traverse the atmosphere. With the increasing use of both composite materials in aerospace vehicle structures and electronic microcircuitry in these craft, lightning, whether natural or triggered, can have catastrophic effects on such vehicles. Yet, specific techniques for forecasting the likelihood of lightning occurrence are not routinely taught as part of the formal meteorological academic curriculum, and forecasters must learn by experience the approaches to lightning forecasting. Thus, the AIAA Atmospheric Environment Technical Committee (AETC), at the suggestion of one of its members, LTC Richard Babcock, agreed to organize and conduct a special short course on lightning forecasting to be presented by some of the foremost experts on this subject at a two-day meeting held on July 19 and 20, 1988. Simuflite Training International Division Systems agreed to host the special short course at its Dallas-Ft. Worth Airport facility. The NASA Earth Science and Applications Division has underwritten the costs associated with the special short course as a service to the community.

The proceedings were videotaped by courtesy of the Air Force and a condensed version of the special short course will be distributed to anyone requesting it for the cost of the duplicating medium.

The NASA point of contact is John S. Theon, Code EET, NASA Headquarters, Washington, DC. The special short course on lightning forecasting was conducted in the belief that it would provide valuable information which may save lives and property from loss to lightning.

John S. Theon
October 1989

INDEX

5WW/FM-88/003

5TH WEATHER WING FORECASTER MEMO

LIGHTNING DETECTION SYSTEM ACQUISITION AND APPLICATION

5 WW/DNS

NOVEMBER 1988

This forecaster memo is intended to shed light on the myriad of Lightning Detection Systems (LDSs) and Lightning Detection Networks (LDNs) currently and soon to be available. This forecaster memo is not an indorsement of any system or network, but simply an attempt to identify the different LDSs and LDNs while discussing their strengths and weaknesses. After a brief introduction, the forecaster memo is broken into sections which can be reviewed by the reader for a total and complete understanding, or a particular section may be read for the desired information contained in that section.

Thanks go to Lt Col Stephen Savage, Lt Col Harold Schmitt, Lt Col Kenneth Hertzler (Ret), Maj Richard Peer, and Ms Betty Burton for their assistance in preparing this forecaster memo.

PRINCIPAL AUTHOR: Capt John D. Murphy 574-5968 - 5909

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4WW..........	1	USAFETAC/LD..........................	5
5WW..........	57	AWS/DNTS.............................	1

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CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

The detection and warning of the existence of lightning, particularly cloud-to-ground lightning, has many practical applications in both the civilian and military communities. Lightning kills more people in the United States each year than tornadoes, floods, or hurricanes. However, because lightning deaths typically occur one at a time, they rarely attract nation-wide attention as do the more spectacular storms which may kill hundreds and cause millions of dollars in damage. In addition to the cost in human life and injury caused by lightning, thousands of dollars are lost and production is wasted by work stoppages resulting from the occurrence or potential for occurrence of lightning. This latter problem is of particular concern to Air Force Commanders and managers as a warning or advisory for lightning typically stops all flight line activity, terminates computer operations, or necessitates a switch to back-up power to prevent surges and outages from potential strikes.

Because of the destructive nature and costs of lightning strikes, there have been on-going attempts to detect and warn of their occurrence. As a result, several means of detecting lightning activity have been developed, and since 1976, more than 3/4 of the United States has been covered by lightning detection sensors. Similar effots have created detection networks in other countries including Canada, Australia, Norway, Sweden, Mexico, South Africa, Japan, Hong Kong, and the Peoples' Republic of China.

Over the past ten years, several federal and state agencies, public corporations, and private concerns have taken advantage of lightning detection technology to provide warning to and protection of critrical operations. Most of these acquisitions occurred, however, independent of any meteorological needs. They were, instead, in response to unique operational requirements such as protecting airports, rocket launch sites, nuclear power plants, and electric utilities.

Today, the primary user and operator of one of the largest lightning detection networks in the country is the Department of the Interior's Bureau of Land Management (BLM). In cooperation with the US Forest Service, the BLM operates a vast lightning location network in the western US to determine the location of lightning strikes within National and State forest preserves. Such knowledge can lead to early detection and fighting of lightning caused forest fires. Since 1982, BLM data has been disseminated in real-time to National Weather Service Offices in the Western Region via the Automated Lightning Detection System (ALDS) operated by the National Weather Service Forecast Office (NWSFO) located at Boise, Idaho. Detachment 18, 25 Weather Squadron is currently the only AWS unit with direct access to ALDS data.

Because knowledge of lightning activity can provide valuable information on the development, movement, and intensity of electrical activity within an area, several companies are conducting ongoing application-oriented research to determine the practical application of data from lightning detection networks (LDNs). One example of such research, data from the State University of New York at Albany (SUNYA) east coast network is being evaluated at the FAA's Washington Air Route Traffic Control Center in Leesburg, VA and at the NWSFO at Albany, NY.

2.0 LIGHTNING GENERATION

2.1 CHARGE FORMATION. There are a number of theories regarding charge separation in thunderstorms. Included among them are ion capture, freezing effects associated with impurities, induction, and charge transfer during particle collisions. One of the more widely accepted theories is based upon phase change relationships of water. Whenever hail, ice crystals, and super-cooled water droplets are present in the same region of a cloud, that region often becomes electrically active. Hail and supercooled water droplets tend to accumulate negative charge, while ice crystals accumulate positive charge. Convective currents within the cloud then tend to separate the charges with the ice crystal's and positive charge concentrated in the upper region of the cloud and the negatively charged hail and super cooled water droplets in the lower and middle cloud regions (Figure 2.1). The electrical charges in a convective cell begin to polarize late in the growth stage of a towering cumulus, as significant updrafts develop. Lightning activity begins only after the development of a deep cumulus cloud with strong enough vertical motions to separate the various hydrometeors and produce charge separation. In addition to the primary concentration of charges within the thunderstorm cloud, there are other pockets of lesser charges throughout the cell; for instance, a small concentration of positive charge is often found in the base near the strongest updraft/downdraft boundaries (See figure 2.1).

2.2 LIGHTNING INITIATION. As convective and gravitational influences continue, the heavier, negatively charged hail and super cooled water droplets concentrate in the lower section of the cloud, while the lighter, positively charged ice crystals accummulate in the upper portions. Increased negative

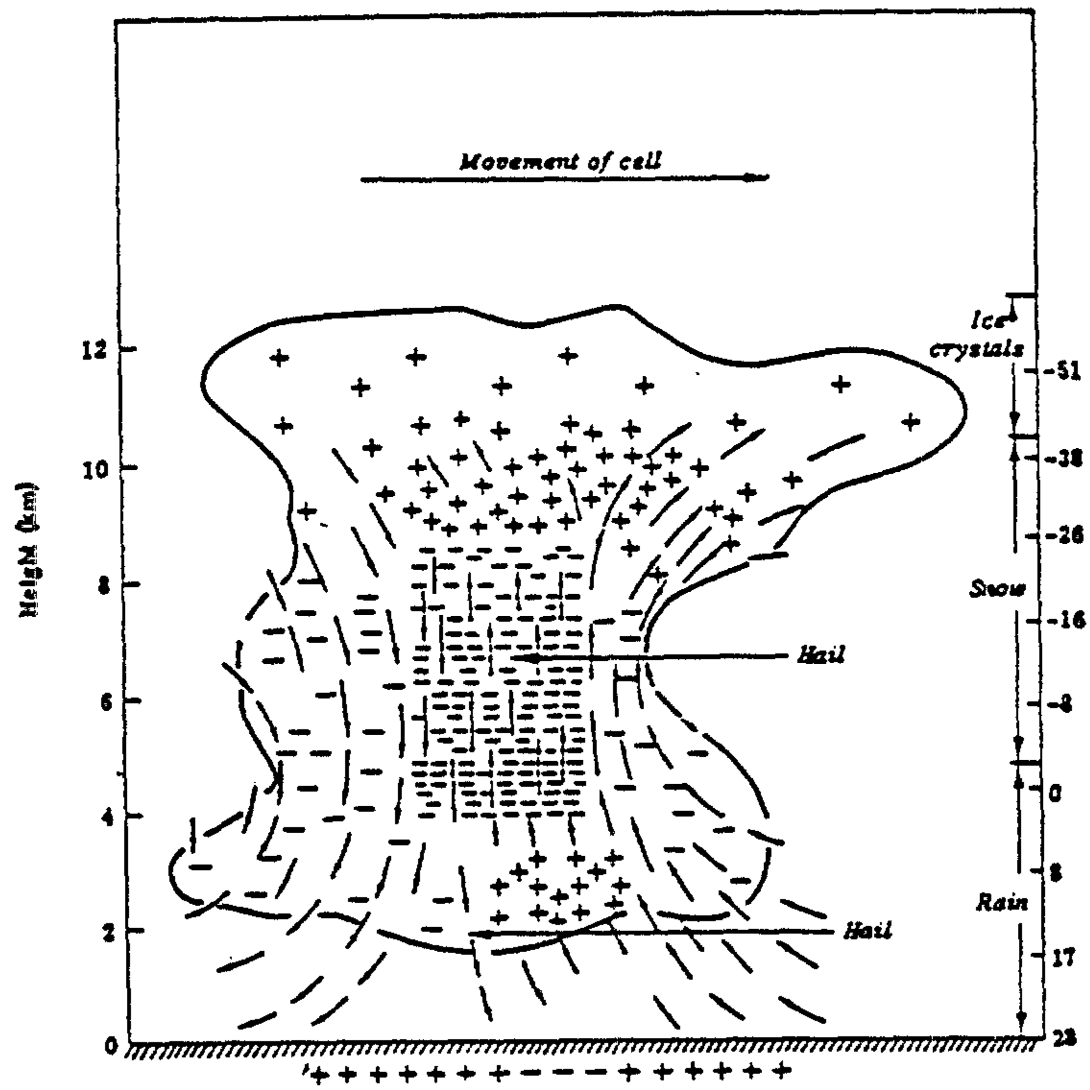


Figure 2-1. Thunderstorm charge distribution (after L.B. Loeb, Modern Physics for the Engineer p330. McGraw-Hill, New York, 1954).

charging in the lower cloud induces an equal positive charge in the earth below.

The area of individual positive charge in the earth moves with the storm. As the charge difference increases between the earth and the cloud base, positive charge begins streaming into higher points on the ground below (trees, towers, etc). The first breakdown in the electric field probably occurs between the pockets of lesser charge within the cloud mass itself. Intra-cloud lightning may develop between the negative center and the small positive area in the cloud base, transferring even more negative charge to the base. When the charge difference between the cloud base and the ground becomes strong enough (approximately 10^6 volts/meter), the electric field breaks down and cloud-to-ground (CG) lightning results (Figure 2.2).

2.3 THE LIGHTNING STRIKE. The first step in the CG strike is the development of the "step leader" (Figure 2.3A). The leader is a core of negatively charged particles which carries the potential of the initiating point within the cloud. The leader moves quickly (on the order of 2×10^5 meter/second), but not continuously, advancing in approximate 50-100 meter steps. The brief hesitations are believed to be due to the recharging of the tip of the leader with charged particles from the cloud base.

Luminosity of the leader is low and usually not visible to the unaided eye. The leader seeks the path of least resistance and may branch several times. When the main branch of the leader approaches to within approximately 50 meters of the ground, the electrical field becomes so strong an upward streamer of positive ions rises to meet it. When the positively charged

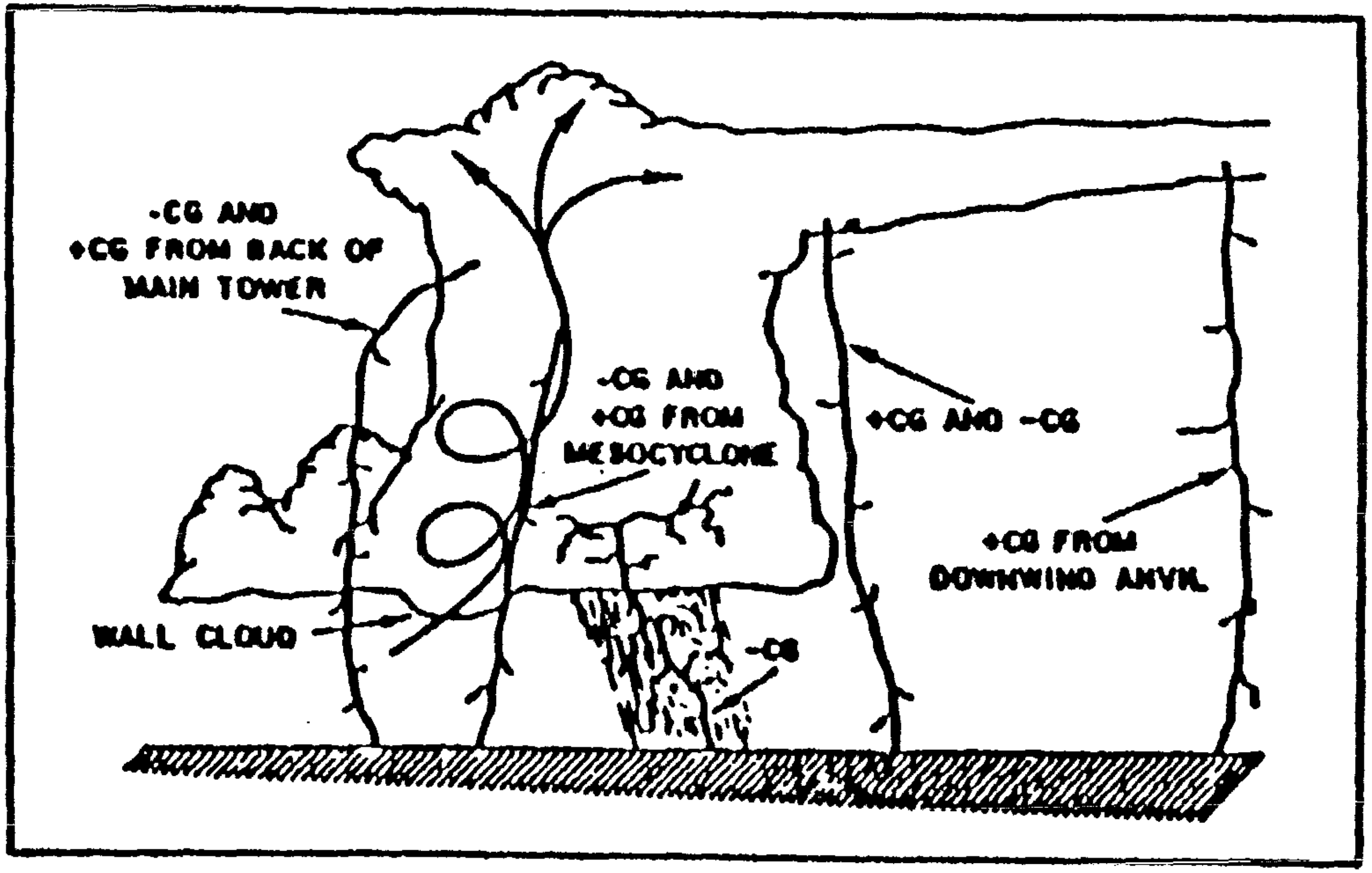
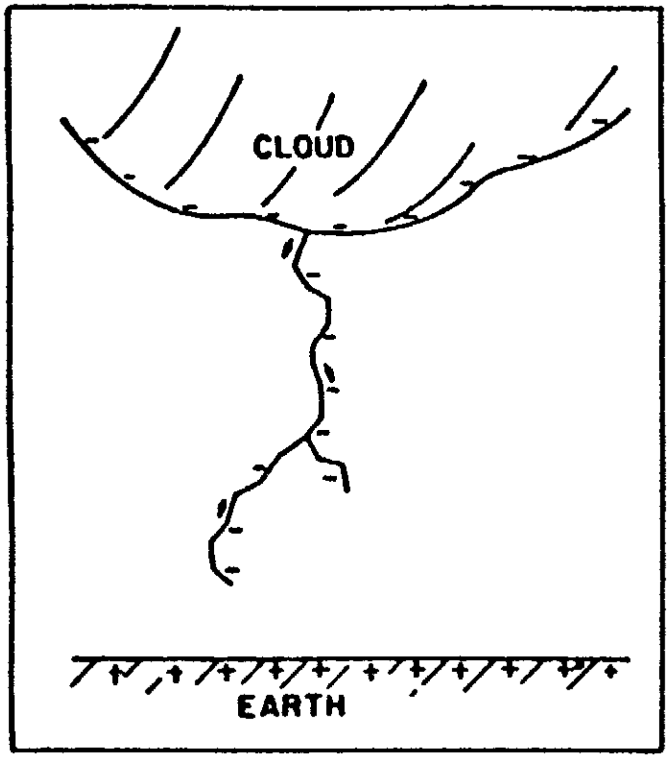
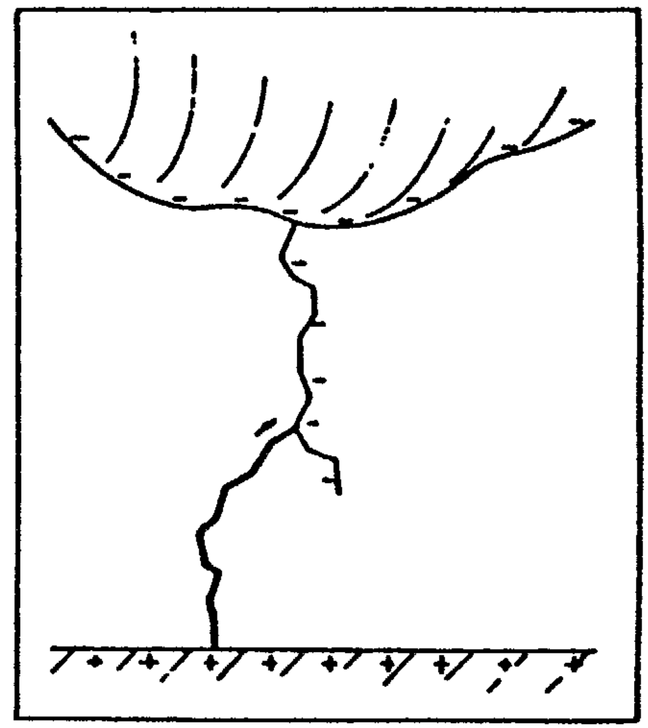


Figure 2-2. Observed locations and polarities of cloud-to-ground flashes (from Rust et al., 1981).



2-3A. Step leader extending from cloud base.



2-3B. Step leader and streamer meet to complete the circuit.

Figure 2-3. Evolution of a lightning strike (from NWS-WR-TA-86-18).

streamer joins the leader, the circuit is complete (Figure 2.3B). The highly luminous return stroke, carrying positive charge, moves rapidly (approximately 5 X 10^7 meters/second) up the ionized channel. Temperatures in the channel approach 3 X 10^{11} degrees celsius. Negative charge is immediately transfered to the ground in the wake of the return stroke, resulting in a net negative charge lowered to the ground (i.e., a negative CG strike).

Upon completion of the return stroke, the ionized channel is at ground potential, but the strike may not be complete. Positive streamers at the top of the channel probe the cloud for additional concentrations of negative charges. If found, a dart leader races back down the ionized channel and another return stroke is triggered. Depending on the concentration of negative charge in the cloud, several return strokes may occur. The time between return strokes varies from 20-200 milliseconds, sufficiently long that the unaided eye can detect the flicker.

It should be noted that many of the step leaders never complete the circuit with the ground; however, they still transfer negative charge toward the ground in the ionized channel.

3.0 LIGHTNING DETECTION SYSTEM DEVELOPMENT AND CHARACTERISTICS

There are two primary systems capable of locating lightning strikes in real time over broad areas. Based on different technologies, one system determines lightning location using direction finding techniques, while the other uses time-of-arrival.

During the mid-1970s, Martin Uman at the University of Florida and Phillip Krider at the University of Arizona were engaged in research on the basic physics and characteristics of lightning. During this research, they discovered that the electro-magnetic radiation from CG lightning had a unique signature. Armed with this knowledge, they designed a magnetic direction finding system capable of detecting this characteristic signature. By combining the unique signature with radio direction finding techniques, the two researches were able to determine azimuth angles to the ground strike point. Uman and Krider used the results of their discovery to found a small company, Lightning Location and Protection, Inc. (LLP) to manufacture and market lightning direction finders. As the technology matured, LLP began connecting two or more of these direction finders into networks so triangulation techniques could be employed to increase strike location accuracy.

Also in the mid-1970s, a British scientist, Rodney Bent, founded the Atlantic Scientific Corporation (ASC) of Melbourne, Florida (now called Atmospheric Research Systems, Inc.), and began marketing a lightning tracking system. Based on time-of-arrival measurements, Bent's system determines the intersection of the spherical hyperbolae defined by the measured differences in time-of-arrival of a lighting flash at three separate stations. ASC established a four station prototype network in Florida in the spring of 1982, forming the basis for its Lightning Position and Tracking System (LPATS).

3.1 DIRECTION FINDERS. Direction finders, such as those provided by LLP, employ two orthogonal magnetic loop antennas and a flat plate electric antenna to sense the electromagnetic field radiated by CG lightning. The azimuth angle of the lightning from the direction finder is determined by the ratio of the signals detected by the loop antennas. Range can be estimated by examining the signal strength received at the detector and applying a range algorithm to calculate strike distance from the detector. To increase both range and azimuth accuracy, two or more detectors may be employed in a network. Lightning location can then be found by using triangulation techniques to determine the intersection of the direction vectors and/or the ratio of the electric field strengths from two or more of the direction finders.

Lightning location accuracy can be affected by a number of factors most of which are related to site location and detector placement. Critical influences include antenna alignment, proper north-south orientation, and location with respect to buildings, trees, and sources of radio or electromagnetic transmissions. Proper grounding is also important. With networked systems, location of the sensors within the network is very important to both range and azimuth accuracy. Sensor location must be carefully selected to allow proper triangulation angles. Networks with detectors too closely aligned in a straight line, result in degraded location accuracy for strikes which occur on the base line. Two sensor networks always suffer from this problem.

3.2 TIME-OF-ARRIVAL SYSTEMS. In a time-of-arrival detection system, the ground stike location is determined by finding the intersection of the sperical hyperbolae defined by the measured differences in the time of arrival of a lightning spheric at three stations separated by 100's of kilometers. A minimum of three stations in the network must detect the lightning signal to obtain an unambiguous location solution within the baselines of the network. Four stations are required for unambiguous solutions outside the network baselines.

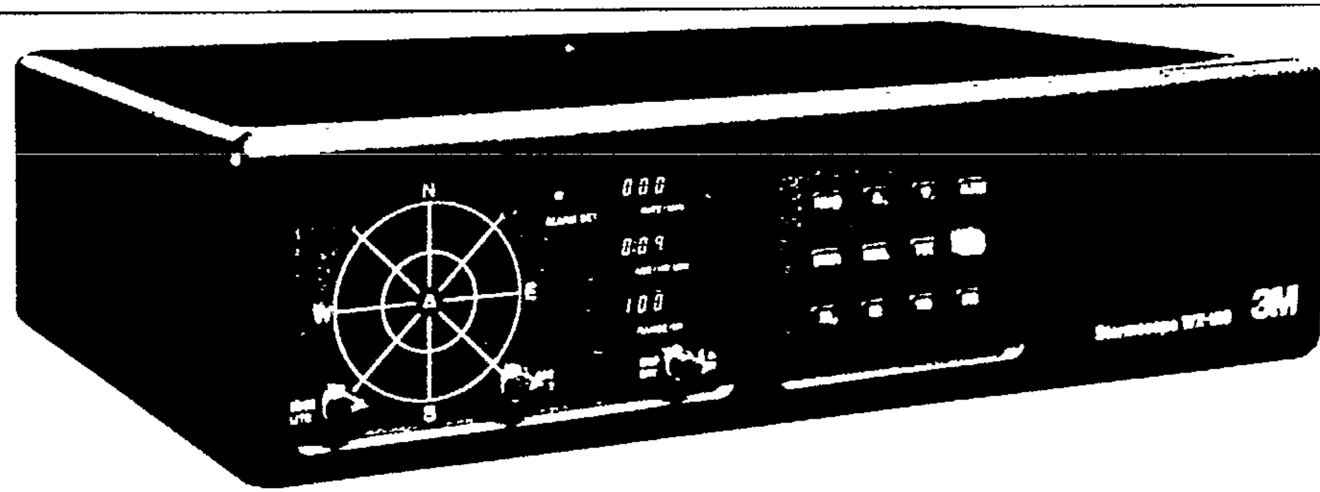
Location accuracy requires precise relative timing of the stations to within a fraction of a microsecond to yield accurate lightning location and avoid confusion between unrelated spherics. This precise timing requirement has been satisfied by using LORAN-C navigation signals to synchronize the time at each of the stations. Site error problems that arise with direction finding systems are usually negligible in time-of-arrival systems which means the electric field antenna, consisting of a simple vertical whip antenna, may be placed in the vicinity of metal objects, other conductors, or on buildings with no serious side effects. Time-of-arrival systems are sensitive to local noise and require an electrically quiet location. Also, because propagation effects on the timing and lightning signals can introduce errors of as much as 1-2 micro seconds, the antenna locations must be surveyed more precisely than for direction finding systems.

4.0 CURRENT SYSTEMS

4.1 SINGLE POINT SENSORS. There are, at present, two competing single point lightning detection systems. Both use direction finding detectors to locate and display lightning location. The two systems will be discussed below.

4.1.1 3M STORMSCOPE. The 3M corporation manufactures a single point sensor, the WX-120 Stormscope, for detecting lightning location and range. Based on a system developed for use in aircraft, the stormscope operates via direction finding techniques to determine azimuth to the lightning flash and an intensity algorithm to estimate range. The stormscope detects electromagnetic signals produced by lightning over 360 degrees of azimuth to a range of 220 miles. All electro-magnetic discharges are detected including those from radio and radar emissions and impulses from intra-and inter-cloud lightning. No attempt is made to apply wave shape matching to discriminate between the discharges. As a result, all flashes, not just cloud-to-ground, are detected and displayed. An undesirable result of this can be a high false alarm rate. Up to 256 discharges, can be displayed at one time, with each discharge signal stored in the order it is received. The information is presented on a circular screen in the form of one dot for each discharge (Figure 4.1). When the 257th discharge occurs, the oldest dot is removed from the display and the newest takes its place. Any dot more than four minutes old is removed automatically.

Clusters are used to locate thunderstorm activity. One or two dots appearing on the display do not represent an active thunderstorm. Two



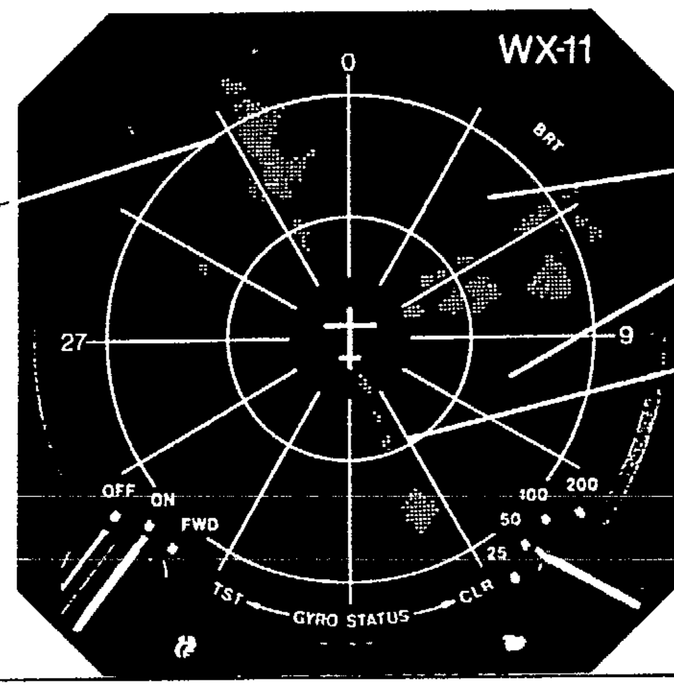


Figure 4-1. The WX-120 Stormscope (top). Stormscope Data Display (bottom).

phenomena associated with the stormscope are radial spread and splattering. Radial spread generally occurs when a thunderstorm is occurring just beyond the maximum range of the range scale used. It is manifested by a stream of dots trickling inward toward the center of the screen, tapering toward the center in a pie-shaped pattern. Splattering occurs when discharges occur within about three miles of the detector, and appears as random splattering of dots across the entire display.

The stormscope offers good azimuth resolution; however, the same factors which tend to produce a high false alarm rate also can contribute to poor range resolution. Specifically, keying off all electromagnetic emissions, including those of intra- and inter-cloud discharges, presents problems in resolving range to the discharges; because, unlike a vertical CG stroke that has a specific ground terminus and, therefore, range, an inter-cloud stroke may extend horizontally over 10 to 20 miles. In addition, only amplitude decay of the discharge is used to determine range over the entire detection range of the system. This tends to lead to less range accuracy than the process of shape matching used by LLP. In a search of 3M literature on the stormscope, we could find no claim regarding stormscope range accuracy.

The stormscope costs $12,150 to purchase. Maintenance is provided by the manufacturer at a flat rate of $300 per repair with the user mailing the broken system to stormscope for repair (about 5 days on average to repair, plus mailing time). Loaner systems are available.

4.1.2 LIGHTNING LOCATION AND PROTECTION (LLP). LLP produces two single point lightning detection systems, the model 420A and model 430. Both systems use the same detector, the 420A; however, the model 420A has only a printed output produced on a dumb printer, while the model 430 uses a color CRT to display thunderstorm location (Figure 4.2). It is possible through a software change to have both a dumb printer and the color CRT attached to the same sensor. This could have advantages as will be seen when the printer and CRT output are discussed later. The model 420A sensor uses a wideband antenna and receiver to sense both the magnetic and electric fields radiated by all lightning discharges; however, the sensor has been designed to reject all signals which do not have the waveshape characteristics typical of return strokes in cloud-to-ground lightning. This processing insures signals from non-lightning background noise sources such as radio and radar emsissions and impulses from intra-and inter-cloud lightning are rejected, and leads to a very low false alarm rate.

The sensor measures direction to the lightning ground strike point using signals from a pair of orthogonal loop antennae. Direction to the lightning is computed by sampling the north-south and east-west components of the lightning magnetic field at its initial peak. In addition to measuring the direction to each lightning strike, the sensor also measures and stores several amplitude and shape characteristics of the lightning which are well correlated with distance. Shape characteristic matching correlates very well with range within 30NM and results in good range accuracy within that distance. At ranges greater than 30NM, only amplitude matching is used to determine range. This results in a degradation of the range accuracy to a claimed ±20 percent from 30NM out to the maximum range of the sensor.

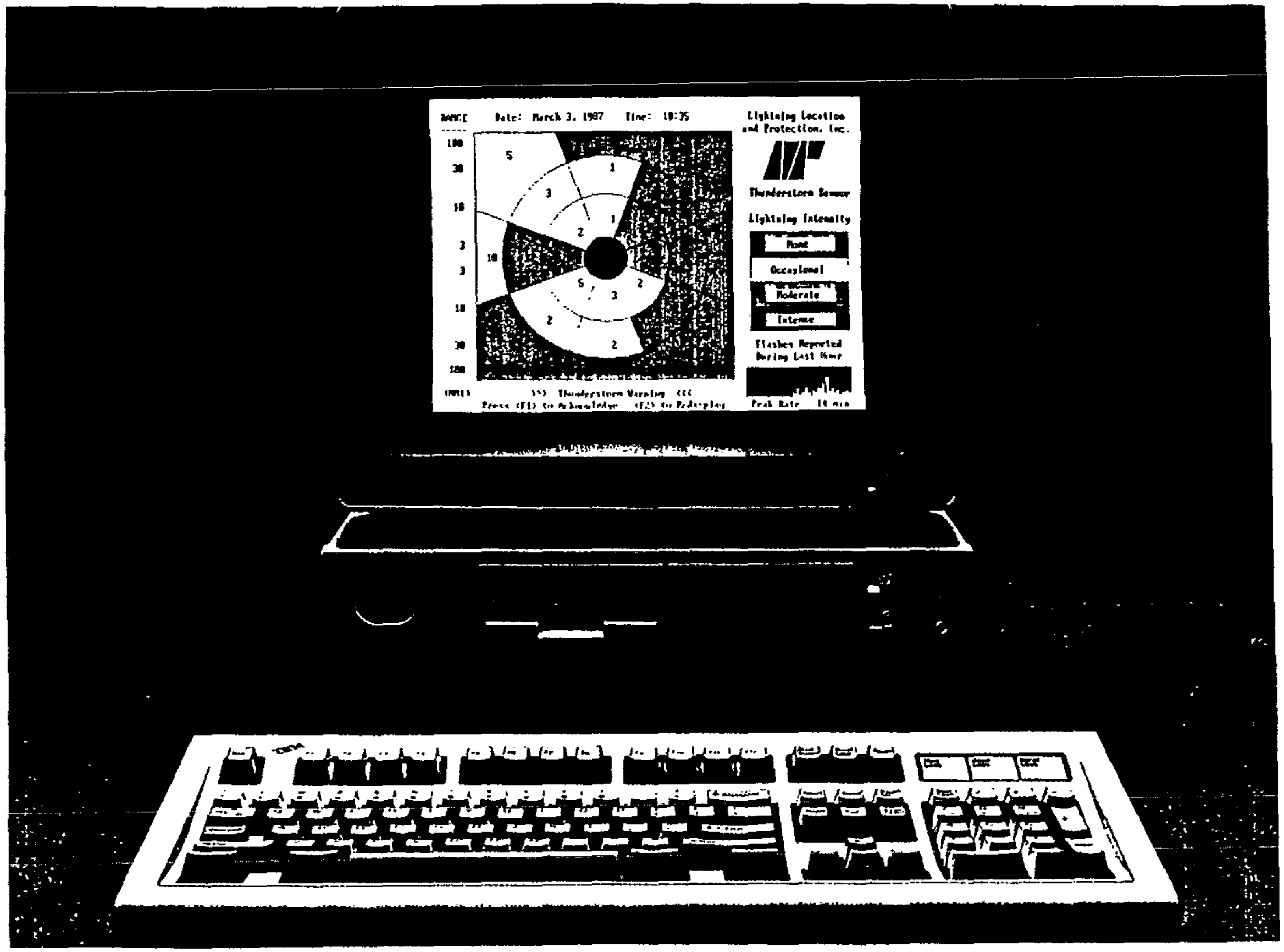


Figure 4-2. LLP model 430 display monitor.

Because the 420A measures range to only the CG stroke and not intra-and inter-cloud discharges, range accuracy is enhanced as only range to the vertical CG stroke need be considered. Range estimates and range averaging to horizontally extended inter-cloud discharges are not part of the range solution as these discharges have already been rejected. Once each minute, the sensor microprocessor examines the amplitude and shape data for all flashes within a specific time (typically 15 minutes) and computes the ranges of the thunderstorm(s) on an octant by octant basis. A minimum of six flashes in any 15 minute period is required to compute storm range. Ranging accuracy improves as the storm flash rate increases because more flashes are available for processing.

As previously mentioned, there are two methods of displaying the lightning data. The model 420A offers only alphanumeric data displayed via a dumb printer. Three messages are generated:

1. Present weather message.
2. Extended message.
3. Sensor status message.

Only the first two messages will be discussed.

The present weather message contains the sensor time, date, an indication of whether or not thunderstorms are occurring within a user prescribed radius (usually within 10NM, a T is displayed; if no thunderstorms are within 10NM, the field is blank), and a series of abbreviated remarks which describe the local thunderstorm conditions. The message appears as in the below example:

18:55 8/15/88 T TE05B41 FQT LTGCG SW-NW AND NE

The extended message provides a summary of the processed lightning flash data which was used to compose the present weather message. An example is given below:

17:18	6/20/88	LTGCG	NE-E-S
OCTANTS	FLASHES	RANGE	LIMITS
NE	2	-	-
E	5	-	-
SE	6	12	36
S	42	8	42

Flashes specifies the total number of flashes detected in the quadrant indicated and is determined by the number of flashes/15 minutes. Range is the minimum range to the flash in NM, while limits is the maximum range. Note that no range is given for the NE and E quandrants because there were fewer than six flashes.

The model 430 uses the same detector but substitutes a color CRT display for the dumb printer. The center of the CRT display is the sensor location. Concentric range circles are located at 0-3 miles (can be adjusted to 0-5 miles), 3-10, 10-30, and 30-100 miles. The circle is further divided into octants. Color coding is used to depict the level of flash activity within each octant/range zone per the following table:

	RANGE ZONE		
COLOR	3-10	10-30	30-100
Green	None	None	None
Yellow	1-5	1-10	1-50
Orange	6-10	11-20	51-100
Red	$\leq$11	$\leq$21	$\leq$101

Flash count numbers are displayed in each octant/range zone.

In the 0-3 mile range zone located over the sensor, yellow is displayed with no flash count if 2 or 3 adjacent octants are active, orange if 4 or 5 adjancent octants are active, and red if 6 or more adjacent octants are active. If a flash(es) occurs overhead, the center goes immediately red and displays the flash count.

If you will remember from section 2.0, each lightning occurrence consists of the initial stroke and perhaps several return strokes. Flash counts displayed in the octants count each stroke and any return strokes associated with it as one flash rather than counting each return stroke as a separate lightning occurrence. On the other hand, the Stormscope counts each initial stroke and each associated return stroke as a separate occurrence. This gives large numbers of data points on the Stormscope display and can produce radial spreading.

Through some minor software changes, it is possible to have both the dumb printer and the CRT display. The advantage of this is contained in the extended message in that you now will not only have the flash count but also the approximate maximum and minimum ranges of the lightning strokes displayed for each quadrant. The 420A detects both positive and negative strokes. Again, through some software changes it is possible to have these displayed. There is some advantages to this as will be discussed in section 5.0.

The model 430 costs $21,900 to purchase while the model 420 with dumb printer is $11,900. A maintenance contract is provided by LLP for a fee of $1,900 per year for the model 430 or $1,190 for the 420. If you don't want the maintenance contract LLP will make reparis for a flat fee of $300 per repair.

4.1.3. SYSTEM COMPARISONS. There are essentially two single point lightning detectors available today, the 3M Stormscope and the LLP 420A/430 Thunderstorm Detectors. Honeywell also is reported to be marketing a system similar to the stormscope, and field mills can be used to detect lightning potential. We have no information on the Honeywell system. Field Mills will be discussed separately in section 4.3.

The 3M Stormscope offers basic lightning detection capability. Its azimuth accuracy is good; however, its range accuracy is highly suspect due to the detection procedures used...all strikes used and the use of amplitude measurements only in the range calculation. The system also suffers from a high false alarm rate as electromagnetic discharges other than those associated with lightning are detected and recorded by the system.

The LLP 420A/430 combines good azimuth accuracy with good range accuracy within 30NM of the sensor. Enhanced range accuracy close in results from application of both amplitude and shape characteristic measurements which are well correlated with range. Outside 30NM, range accuracy deteriorates as only amplitude correlations are used; however, accuracy remains at approximately ±20 percent of the reported value. The sensor applies waveshape matching to reject all electromagnetic impules detected other than those correlated with cloud-to-ground lightning which produces a very low false alarm rate.

With any single point detector, antenna location and exposure is highly important to achieving good range/location accuracy, perhaps even more so than with networked system. Various factors, including proximity to buildings, trees, fencing, terrain, and other radiation sources, influence the path of the electromagnetic impulse or input spurious signals into the system. Proper grounding, orientation, and cable placement also affect accuracy. Proper site selection is, therefore, critically important. When procuring these systems, be sure you have a suitable site available, and be sure either the vender will install the antenna for you or you have made arrangements to ensure someone else installs it properly.

4.2 NETWORKED SYSTEMS. Networked systems operate by linking two or more lightning detectors to a central processor. The processor then calculates lightning location using either triangulation or time-of-arrival techniques depending upon the lightning detector used. Position locations are then transmitted to the network subscriber via land lines or satellite circuits and displayed on a CRT monitor. Lightning locations are usually depicted by dots and are often color coded to differentiate between current and past strikes. Colorized time increments are often adjustable; i.e., 15 minute increments, 1 hour increments, etc. Presently, there are a number of different lightning detection networks operated by both government agencies and private concerns using either LLP or LPATS sensors. These networks will be discussed in the next few paragraphs.

4.2.1 NOAA/ERL/NSSL NETWORK. The National Severe Storms Laboratory (NSSL) uses LLP sensors to cover most of the Great Plains region. The network began in 1978 as a transportable system within the NOAA/ Environmental Research Laboratories (ERL) to study the effects of cloud seeding on lightning production and to study lightning climatology in Florida and Oklahoma for the Nuclear Regulatory Commission. In 1980-81, the network was expanded to four stations and installed permanently in Oklahoma by NSSL. In 1985, three more direction finder stations were added to improve coverage (see figure 4.3).

Data application from the network has been directed primarily toward research; however, data is being provided to the NWSFO in Norman, OK for trial use and is also incorporated into the SUNYA network data base.

During 1986 and 87, this network was used by NSSL (MacGorman and Rust) for detailed comparison of the LLP and LPATS capabilities using ground truth data gathered from two all-azimuth television systems and from

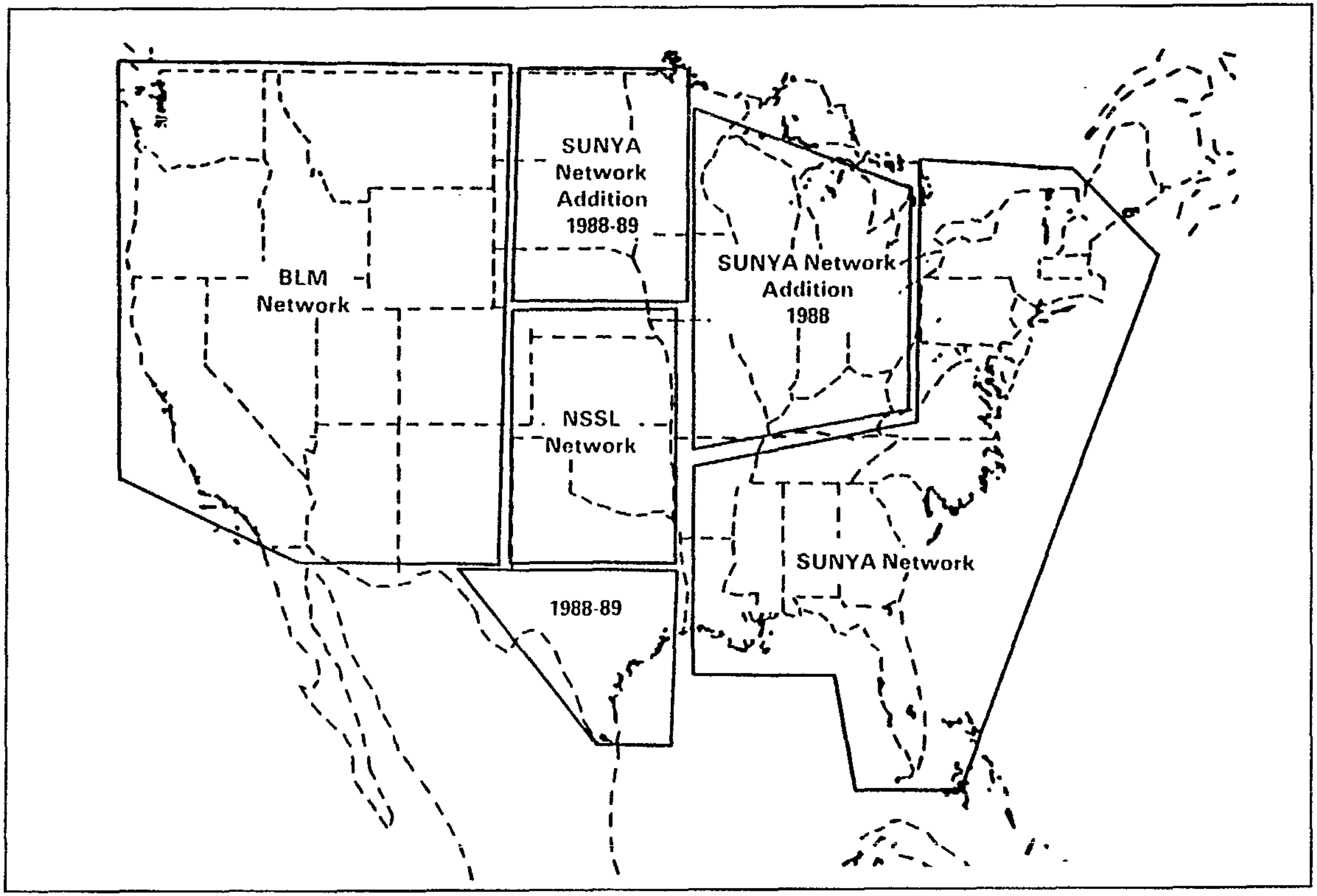


Figure 4-3. Experimental National Lightning Detection Network with boundaries of SUNYA, BLM, and NSSL coverages (from Preliminary National Plan for Lightning Detection Systems, 1988).

television cameras installed on the NSSL mobile laboratory. Study results will be discussed later in sections 4.2.3 and 4.2.5.

4.2.2. BLM NETWORK. Operated by the Department of the Interior, Bureau of Land Management (BLM), the network is the largest lightning detection network managed by a federal agency. It was initiated in 1977 to assist in the early detection of lightning caused forest fires. The system provides coverage of 11 western states using 33 LLP detectors (see figure 4.3). Data is fed into computers located at the BLM's Interagency Fire Center at Boise, Idaho where it is processed and displayed (see figure 4.4 & 4.5). Data is also provided to the NWSFO at Boise for entry into the NWS's Automated Lightning Detection System (ALDS) which provides access to NWS Offices in the western region. Detachment 18, 25 Weather Squadron located at Mountain Home AFB, Idaho has access to ALDS data. BLM network data is also available in the NWS AFOS system. Raw direction finder data is sent to the SUNYA system as part of the national network demonstration where it is available to federal agencies through the SUNYA network.

4.2.3. SUNYA NETWORK. In 1981-82, Dr. Richard Orville of the State University of New York at Albany (SUNYA), with the encouragement and support of the National Science Foundation, started a small lightning location network in the northeast US. Realizing the potential value of the network, others, including NASA, contributed toward network expansion. Today, the system is mainly supported by the electric power industry through the Electric Power Research Institute.

The SUNYA network uses LLP direction finder sensors operated at

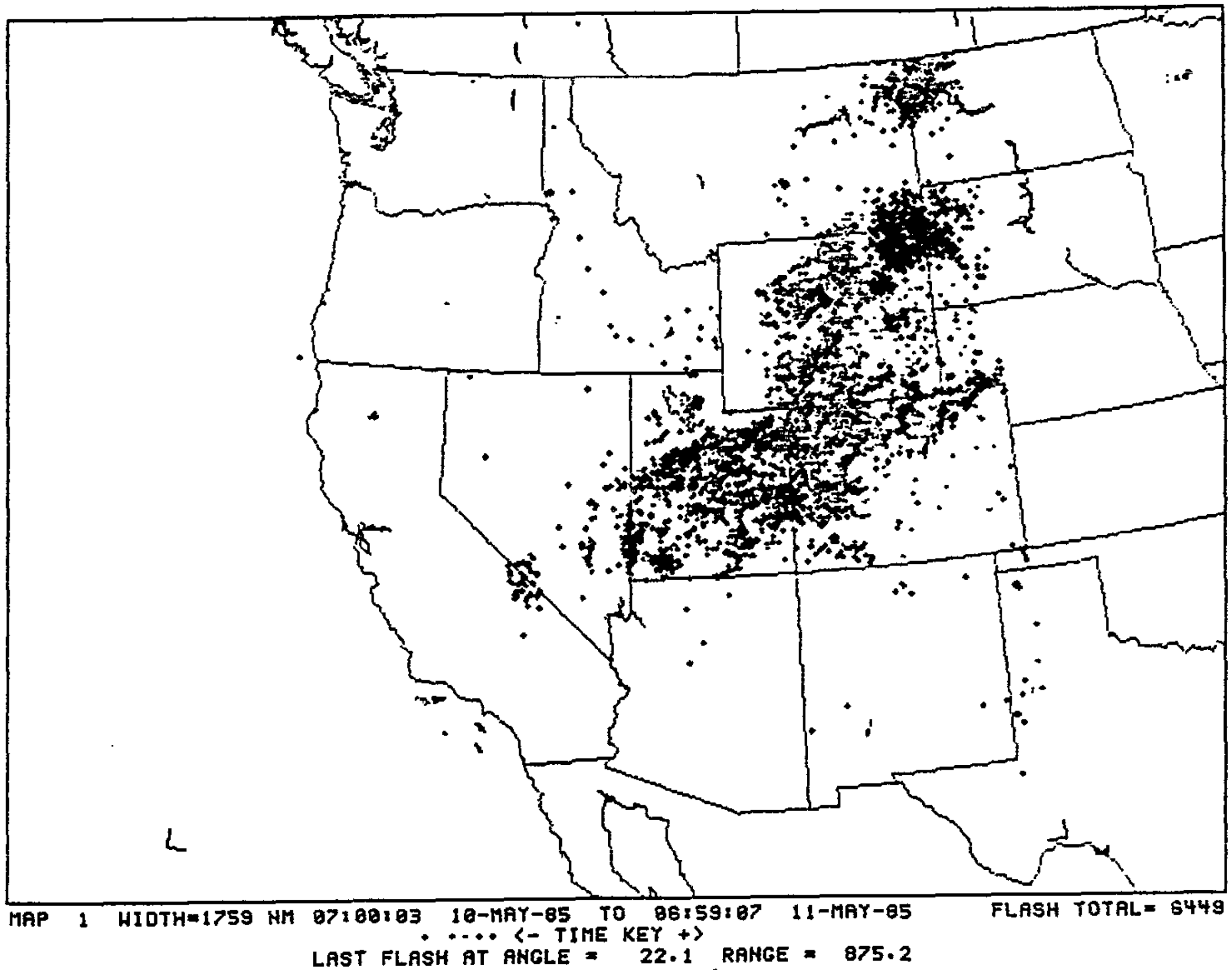


Figure 4-4. Sample LLP lightning display over BLM network. Twenty-four hours of data, 10-11 May 1985.

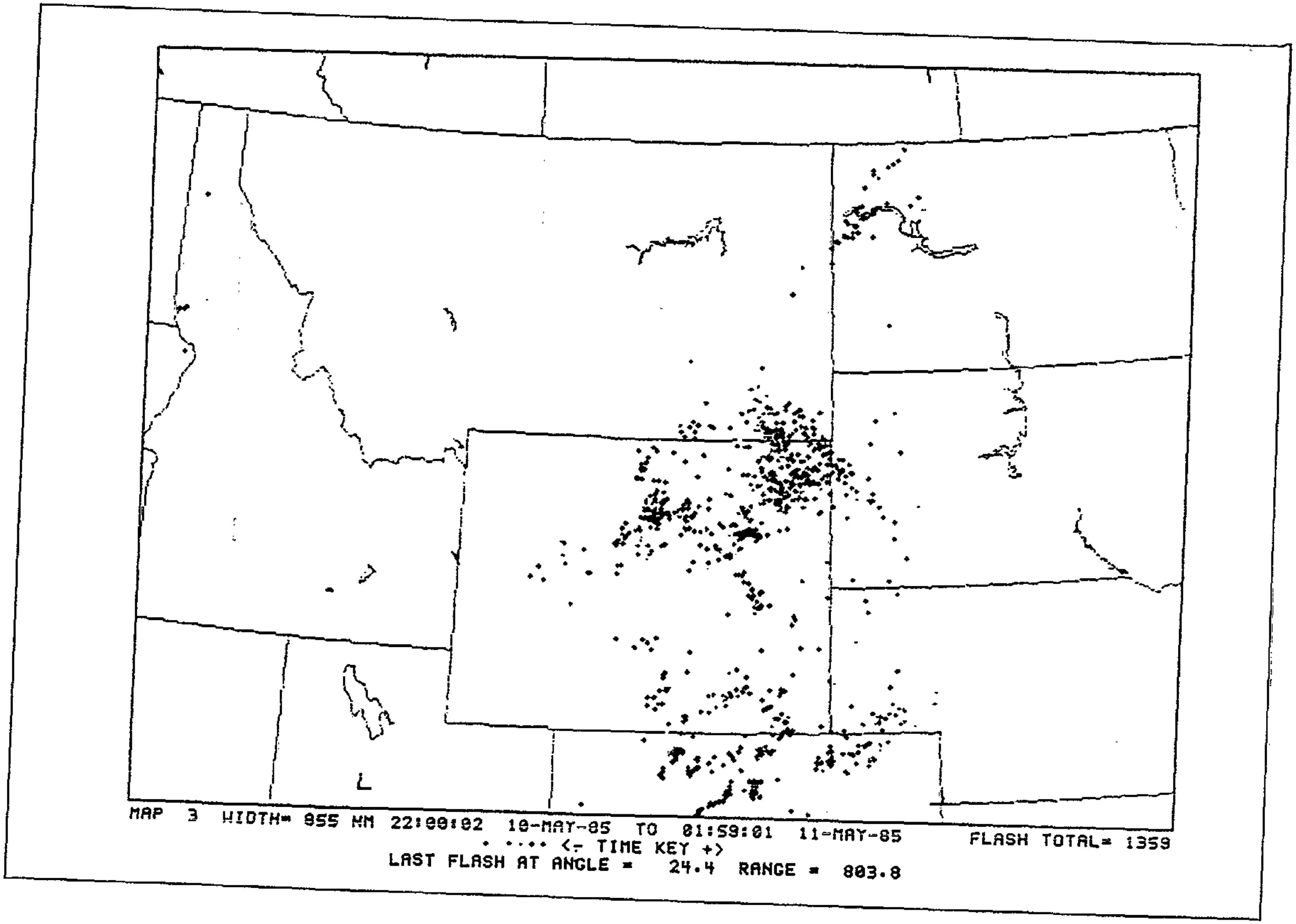


Figure 4-5. Sample LLP lightning display over BLM network. Four hours of data, 10-11 May 1985.

high gain for a nominal detection range of 400KM. By the end of 1988, nearly 40 sensors were inplace providing coverage for the east coast, southeastern states, and the upper midwest (see figure 4.3). Data is also collected from a number of local systems operated by various federal agencies and the private sector to supplement coverage. Raw data from these sensors is collected, processed, and archived at the SUNYA operations center in Albany, NY. Data and/or products are then made available via satellite over a dedicated user circuit to network subscribers. SUNYA now has access to both the BLM and NSSL networks which provide a near nation-wide lightning detector network. Data from these two networks is also processed at Albany and provided to subscribers over the user network.

The SUNYA system consists of a computer, monochrome monitor, and color monitor. The monochrome monitor displays system control information, menus, etc., while the color monitor is used for the actual lightning displays. The basic map display is an outline of the US with state boundaries. The map has detail down to 1KM and the capability to zoom down to any desired level. Up to 121 labels can be added to the map with the level of detail increasing as the scale is increased. County lines are availabe for the 48 contiguous states. SUNYA provides software that will allow the user to place his own simple polygon overlays onto the basic map. This could be used to add range areas and routes to the basic display. More detailed overlays can be created by SUNYA for a small charge. Generally SUNYA creates the first overlay for free. The system receives the most recent lightning locations every eight seconds for processing and display. Up to 44,000 flashes can be retained in memory for instant recall and display. Both positive and negative strokes are identified.

A complete system, including computer, satellite dish, and monitor costs $9,350 plus $200 for shipping (one-time cost). One satellite dish can support up to four systems as long as the systems are within a few miles of each other. Additional systems are $6,750 each. An additional one-time cost of $1,250 plus travel costs is charged for SUNYA to install the system. This fee includes a one day training session on system use. Recurring communications costs of $7,000 annually are for the satellite linkage. Since the user is a federal agency, there are no access fees.

In 1986-87 NSSL conducted a comparison of an LLP network versus an LPATS network. Results of the LPATS test are discussed later. For the LLP system, it was found that the mean location accuracy was 2-3km within the network with an average 100km baseline between sensors. Location accuracy degraded to about 10km at 250km range. Location error outside the network increased fairly rapidly and depended somewhat on the orientation of the region relative to the network. Detection efficiency out to 250km was found to be 50-70 percent with efficiency decreasing relatively slowly with range. The LLP system had no detectable problem with false detection. Mean location accuracy in the eastern portion of the SUNYA network is 3KM at the center of the network decreasing to 10KM at the edges. In the BLM portion of the network, mean location accuracy is on the order of 5KM degrading to 10KM or slightly worse at the edge. Location accuracy degradation in the BLM sector is the result of a larger base line. Detection efficiency is 70 percent.

4.2.4 US NAVY NETWORK. The US Navy is developing a lightning detection network with initial operation scheduled for 1988. Employing LPATS sensors, the network will consist of 18 master stations and 40 remote sites. The network will provide coverage along the East and Gulf coasts and throughout the Mississippi River Valley. In addition, two sites will be located on the west coast in northern California. Unfortunately, the sites are not linked to form a national network, rather a site(s) transmits data to only its master station. Similarly, information at each master station is not transmitted to other master stations. Each master station operates as its own mini-network. Under the current plan, there is no data tie in for the Air Force; however, Air Force units could obtain data by modem if tie-in and display equipment were purchased and access negotiated with the Navy master station. Approximate cost is quoted at $16,000 for the equipment plus probable communication costs and a possible contract maintenance charge.

4.2.5 R-SCAN NETWORK. The R-Scan Corporation is installing a nation-wide commercial lightning detection network using LPATS sensors. Over 70 sensors will be used in forming the network. By the end of 1988, the eastern portion of the system was to be completed, with the western half to be finished in the fall of 1989 (see figure 4.6). Rather than one integrated national network, the R-SCAN network is actually composed of 12 mini-networks covering specific geographic regions. Each mini-network will employ 4 to 6 sensors to provide detection coverage in the region. Regionalizing the network is necessary due to the need of a time-of-arrival sensor for precise micro-second timing to determine strike location and the difficulties associated with timing precision over a nation-wide area.

Data is collected and processed at R-SCAN's headquarters in Minneapolis, MN and distributed via satellite to the user. The data is

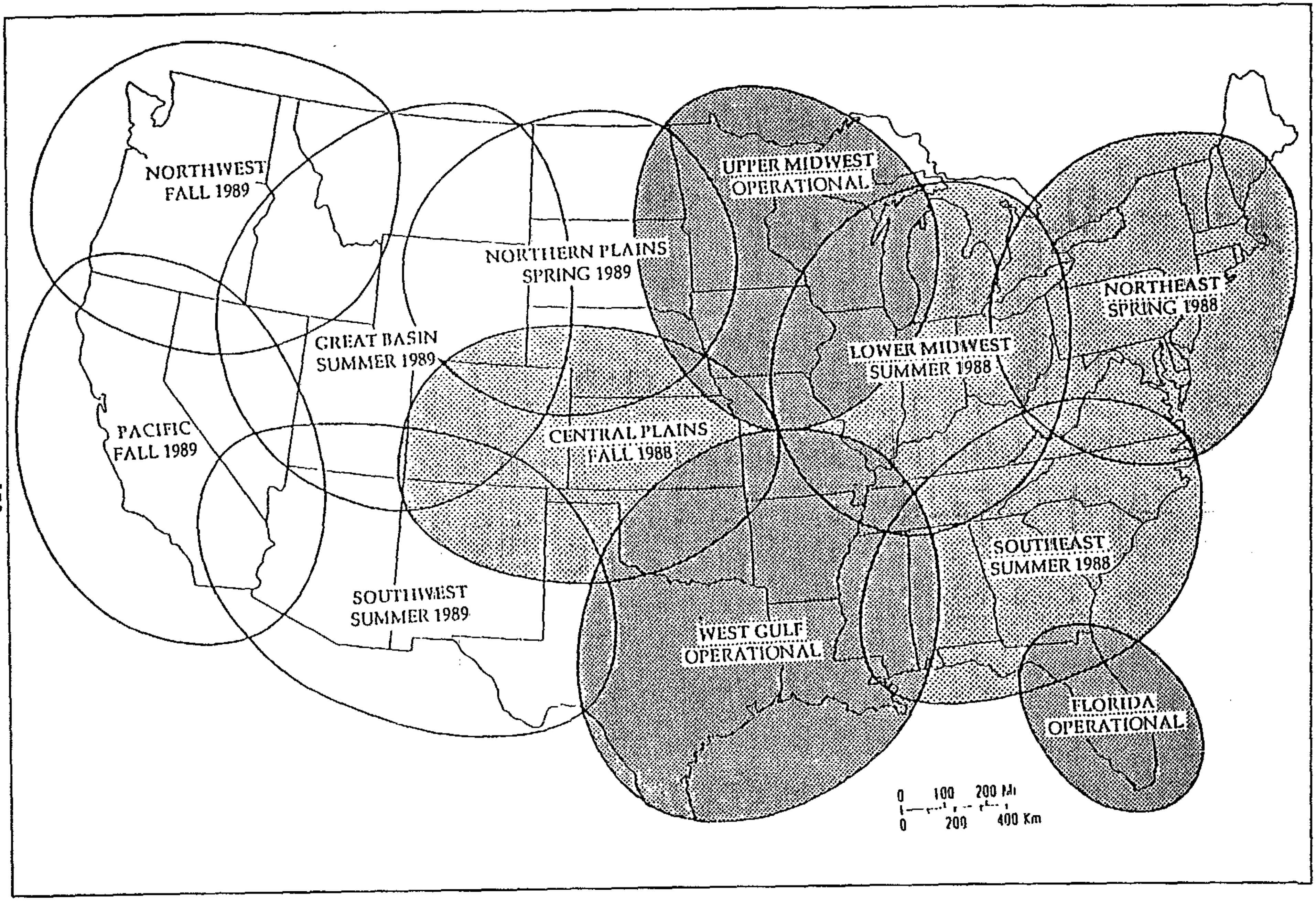


Figure 4-6. R-SCAN network configuration (from the Preliminary National Plan for Lightning Detection Systems, 1988).

displayed on a CRT monitor on maps and overlays provided by R-SCAN. Output for each detected stroke includes date/time, latitude/longitude, polarity, and estimated peak current. Stroke position is plotted on the monitor. Three coverage areas are available, 240 x 240, 480 x 480, and 960 x 960 miles. The center of the display grid is adjustable to any point in the area of the coverage. Costs are $295, $495, and $995 per month respectively for access and a $125 per month communication fee. There is a one-time charge of $595 for the software to run the system and $3,950 for the communication system, antenna, receiver, and control unit. The software was designed to run on the Z-248, so if you already have Z-248s, hardware would cost nothing; otherwise, factor in the cost of a Z-248 or other IBM PC compatible computer.

R-SCAN quotes a location accuracy of 1KM with a detection efficiency of 85 percent for cloud-to-ground strokes. Again, quoting from the research conducted by NSSL; LPATs networks displayed better range accuracy at longer ranges outside the network (a mean error of 8-10km at 300km range) than at shorter ranges inside the network (mean error greater than 8-10km). LPATS detection efficiency was found to be around 40-50 percent out to 250km. The NSSL tests were conducted using three LPATS sensors to compute range. One of the recommendations after the test was that using four sensors would improve both detection efficiency and range accuracy. The system now employed by R-SCAN uses four stations in range calculations. With the addition of a fourth sensor, range accuracy appears to approach that of SUNYA, but detection efficiency remains lower. There may also be a high false alarm rate as R-SCAN cannot use wave form matching as does LLP to discriminate between electro-magnetic discharges (waveform correlation is patented by LLP). Also, there are location accuracy problems at the boundaries of the LPATs regions due to time synchronization problems. Eventually the location accuracy problem will probably be solved as there is nothing inherently wrong with time-of-arrival techniques that would limit their accuracy. The main problems encountered now are time synchronization problems.

4.2.6 NETWORK COMPARISONS. Any discussion of network comparisons really boils down to a comparison of LLP equipped SUNYA versus the LPATS equipped R-SCAN networks as these are the only two choices available.

The SUNYA network offers near nation-wide coverage through incorporation of the BLM and NSSL networks. Location accuracy within the eastern portion of this network (the original SUNYA network) is about 3km on average although within portions of the network with shorter baselines, accuracy is somewhat better and can be as good as 1/2km. In the western portions, where average baselines are longer, mean location accuracy deteriorates to 5km. The NSSL portion of the network has a mean accuracy of 2-3km. Location accuracy degrades rapidly outside the network in LLP equipped networks becoming about 10km on the edges of the eastern network and up to 20km in the western. Location accuracy for any given location is also somewhat dependent upon where you are with respect to the network sensors. Detection efficiency within the network is 70 percent with a gradual decay with increasing range. Because of waveform matching techniques and rejectiom of all electromagnetic discharges which do not correlate to cloud-to-ground waveforms, the false alarm rate is very low.

LPATS networks, such as that operated by R-SCAN, are not true nation-wide networks. Due to the previously discussed limitations on timing accuracy, these networks are operated over a series of smaller regions to provide nation-wide coverage. Mean location accuracy appears to be better outside the network, where it averages 8-10km, than within the network, where it is somewhat less. Detection efficiency is less than that of LLP networks, averaging in the 35-45 percent range, while the false alarm rate tends to be a bit higher due to a greater number of intra-inter-cloud discharges being detected and included in the strikes reported by the sensor(s).

It is important to remember that in any discussion of the merits of these two competing networks/systems there are no absolutes. Each vendor is constantly making changes and improvements to their respective systems. The statistics provided above are based largely on test results from a 1986-87 test conducted by NSSL. Since that time, both vendors have made and continue to make improvements in their networks which continually improve location accuracy and detection efficiency. It is always best to contact the vendor before making any purchase decisions based on range/location accuracy.

4.3 FIELD MILLS. Field mills are designed to detect changes in the charge buildup within clouds. The potential for a lightning strike increases as the electric charge in the clouds increases. When the charge reaches a specific magnitude, generally accepted as 2000 volts/meter, the potential for lightning occurrence is high. Most field mills have an alarm mechanism which can be set at a pre-specified level to warn that the electric field has reached a level where there is high potential for lightning.

The advantage of the field mill is it provides an indication that the first lightning strike from building thunderstorms may be imminent. In this sense, unlike lightning detectors, it has some predictive value. Unfortunately, there are a number of things which can cause large field strength readings on the field mill other than the cloud electric field. Also, there is no good correlation between electric field strength and actual discharge; so one cannot say for sure that with a 2000 volt/meter charge, there will definitely be a lightning discharge. Another problem with the field mill is the relatively small area over which it senses and for which it provides protection. This area is usually limited to a radius of a few kilometers centered on the device. Hence, it requires a large number of field mills to protect large areas. Field mills are relatively inexpensive, which does allow for the purchasing of several sensors if larger areas require protection. Prices generally range from $4,000 to $6,000. Atlantic Scientific Corporation lists its electric field mill at $4,449 in the latest GSA catalog.

5.0 APPLICATIONS

The field of lightning research, aided by the use of individual and networked lightning detectors, is just beginning to reveal ways in which knowledge of lightning frequency, distribution, and polarity may provide valuable information to the forecaster. Lightning data can be used to supplement radar data, satellite imagery, or surface observations to determine whether or not a convective cell is indeed a thunderstorm. In data sparse areas, lightning data may be the only information available for determining thunderstorm presence.

5.1 RADARS, SATELLITES, AND LIGHTNING DETECTION. It is important to remember that radar cannot detect lightning. When the radar operator reports a thunderstorm, he is, in reality, making an educated guess based on certain characteristics of the cell which correlate with thunderstorm activity. Also, the operator can't identify each individual cell and classify it as a thunderstorm or a shower. At best, the operator may identify several groups of cells, but often, the operator just lumps everything on the screen into one category, thunderstorms or showers.

While satellite imagery provides greater coverage than radars, it suffers from being less than real time and from the same problems of identifying which clouds or cells are thunderstorms and which are not. In addition, as the thunderstorms build and mature, the cirrus blow-off soon begins to obscure the individual cell's location, increasing the difficulty of identifying where the lightning is.

Lightning detectors, particularly detector networks, alleviate some of the problems associated with radar and satellite data in that they provide real-time, broad area detection of cloud-to-ground lightning, and they tell us objectively where it is occurring. To put this in perspective, Tables 5.1 and 5.2 list ways in which lightning data supplements radar and satellite data respectively.

5.2 RELATIONSHIP OF LIGHTNING DATA TO THUNDERSTORM DEVELOPMENT. As mentioned previously, lightning data is often the earliest indication of thunderstorm development, possibly preceding first radar detection by as much as 15 minutes, or it may be present in the absence of radar echoes, particularly in the western US. Combining lightning data with radar echoes has shown that the most frequent lightning tends to avoid the highest reflectively cores and is sometimes found on the leading edge of the precipitation core.

During the summer months when thunderstorms have higher tops and stronger intensities, as many as 99 percent of the cloud-to-ground lightning strikes are negative. However, there is evidence that in the winter, the proportion of positive cloud-to-ground strikes increases. Positive cloud-to-ground strikes are of interest to us because of their potential for producing damage to aircraft in flight and/or structures on the ground. As a rule, positive strikes carry more current and have a larger dwell or attachment time, usually with only one return stroke. The combination of high current and lengthy dwell time increases the potential for damage or the likelihood that protective systems will be overwhelmed with, perhaps, catastrophic results. Studies of positive lighting suggest information about

TABLE 5.1

WAYS IN WHICH LIGHTNING DATA SUPPLEMENTS RADAR DATA
(from Ewald, Eastern Region Technical Attachment 87-11(A), June 1987)

1. It gives the entire picture (if networked) instead of viewing 120 to 200NM around the radar site and does so in real time.

2. It identifies line vs cluster configuration. On radar, it is sometimes hard to discern a line, especially if it appears on the edge of the scope.

3. It confirms a radar echo as a thunderstorm. It is not unusual for lightning to be produce by cells with only modest tops, while at other times, cells with much higher tops produce no lightning.

4. Its a great tool for confirming embedded cells are thunderstorms.

5. It gives location and movement in real time. With use of colors (in a networked system) that change every 10 to 15 minutes, it's easy to see movement of cells, clusters, and lines.

6. In areas of high radar ground clutter, lightning detectors can keep track of where the cells are and where they are moving.

7. Lightning detectors can detect lightning before the first echoes appear on the radar.

TABLE 5.2

WAYS IN WHICH LIGHTNING DATA SUPPLEMENTS SATELLITE DATA
(from Ewald, Eastern Region Technical Attachment 87-11(A), June 1987)

1. Its real time, no waiting for a picture.

2. It confirms a convective cloud field viewed on the satellite picture actually contains thunderstorms.

3. It gives thunderstorm location and movement even after extensive anvil cirrus obscures the position of individual cells.

the storm itself. For instance, toward the dissipation stage of the storm, the number of positive strokes seems to increase. Recent research revealed that generally 65 percent of the time when thunderstorms dissipated, there was a gradual decrease in the negative strikes, but no positive strikes. However, 30 percent of the time, positive strikes began to appear in areas of predominantly negative strikes and the radar tops and intensities generally lowered within 20 to 30 minutes. The remaining 5 percent of the time, positive strikes appeared but weak thunderstorms lingered another 2 to 4 hours. Positive strokes are also usually associated with weaker (probably dissipating stage) and embedded (perhaps winter time) thunderstorms. Still other studies suggest a possible correlation between positively charged lightning and the occurrence of micro-bursts.

5.3 OTHER RELATIONSHIPS. Several papers have been written on the occurrence of lightning in hurricanes. In August 1983, hurricane Alicia was observed using cross-baseline interferometers. The recorded electrical activity was noted to be on the equaterward side of the vortex and increased as the storm made landfall. In September 1984, lightning activity in tropical storm Diana was again observed on the equatorward side of the storm near the eye wall. Significant lightning activity was observed just prior to rapid intensification into a hurricane.

Studies of lightning associated with Mesoscale Convective Complexes (MCCs) found ground discharge rates in excess of 1,000 per hour sustained over 9 consecutive hours with peak rates of nearly 2,700 per hour. The most active period was also characterized by the greatest average number of strokes per flash (3-4) and the largest portion of flashes with multiple strokes.

Lightning data have also been used to issue a flash flood watch. In one instance, the lightning pattern displayed on the monitor indicated an almost continuous series of thunderstorms moving into an area. A flash flood watch (later upgraded to a warning) was issued. Such flooding was later reported.

5.4 MEANING FOR THE BASE WEATHER STATION. Obviously lightning detection can be used to identify and locate areas where lightning is occurring. By observing the movement of these areas, it is possible to forecast their arrival over the base or other areas of interest, and in this way, gain a measure of forecasting capability. Used in this way, a lightning detecting system, network or single point, can be used to refine the timing of lightning advisories and thunderstorm warnings. This can have a significant impact on the customer who may be faced with deciding on whether to shut down the flight line, suspend refueling or arming operations, shut down computers, etc. Lightning information over tactical ranges can supplement or take the place of radar data. This can be of particular importance in the western US where conventional data may be sparse (or nonexistent). Knowledge of stroke polarity (positive vs negative) can, according to recent research, provide additional clues as to the stage of thunderstorm development, possible location of downburst activity, or areas to be avoided because of the greater risk of catastrophic aircraft damage should a strike occur.

6.0 ACQUISITION CONSIDERATIONS.

When deciding whether or not to procure lightning detector capability, there are several questions that need to be answered before the acquisition should proceed. These include:

- o What do you or your customer want the system to do; i.e., what is the objective.

- o What are the capabilities of the various systems toward meeting the objective.

- o System costs versus available funds.

- o Equipment performance and reliability.

It is absolutely essential that both you and the supported customer understand exactly what it is you wish to accomplish with the equipment and what capabilities the systems you are investigating have. To ignore this requirement is to risk failure to satisfy the need and to breed customer dissatisfaction. Factors such as, do I wish to protect a point versus a large area, how much location accuracy do I need, what can I afford, and is maintenance available, are all pertinent and need to be answered.

Networked systems provide good azimuth and range accuracy over large areas and are ideal for defending tactical ranges, air refueling tracks, low level routes, and flight corridors to or from range areas. They have the additional advantage of not having maintenance costs nor does the user have to provide maintenance, as maintenance is provided by the network operator. Of course, you are paying for maintenance in the form of an access fee, but because it is spread over a number of customers, it represents a small cost to the individual user. Disadvantages are the continuing access and communications costs borne by the user.

Single sensor systems tend to be less accurate, particularly with respect to range accuracy; however, they can be located close to (or on) the site to be protected which helps overcome this shortfall. The LLP system, at least, does offer reasonable range accuracy within 30 miles of the sensor, and so may be useful for protecting a base complex. Single point sensors are best used for point defense of a small area around the sensor. They can also be moved if requirements change. Another advantage is there is only the one-time purchase cost. There are no access or communications fees. There are, however, continuing maintenance costs, plus a source for maintenance must be found.

Table 6.1 lists the various single point sensors and provides a comparison of their costs and capabilities. Table 6.2 does the same thing for network systems. Figure 6.1 projects the accumulated cost over eight years for each system based on the cost data in Tables 6.1 and 6.2. The cost data were provided by the respective vendors.

TABLE 6.1

SINGLE-SENSOR COMPARISON

SENSOR	COST	DETECTION EFFICIENCY	ACCURACY	FALSE ALARM RATE	COVERAGE	DETECTION
3M STORMSCOPE		Unkn	Azimuth-Good Range-Poor	High	0-220MI	All lightning and extraneous electro-magnetic emissions
One time cost	$12,150 (optional mount $160) plus MTN					
Recurring	($300/repair)*					
LLP 420		70-85%	Azimuth-Good Range-=20%** (Better inside 30NM)	Very Low	0-100NM	+/- Cloud-to-Ground Dumb printer only for displaying output
One time cost	$11,900 plus MTN					
Recurring	$1,190/yr for maintenance contract or $300/repair***					
LLP 430		70-85%	Azimuth-good Range-=20%** (Better inside 30NM)	Very Low	0-100NM	+/- Cloud-to-Ground Color CRT monitor to display output
One time cost	$21,900 plus MTN					
Recurring	$1,900/yr for a maintenance contract or $300/repair***					

*There is no maintenance contract.
**Ranging acçuracy improves as the storm flash rate increases up to +/- 1nm.
***Equipment is very reliable - paying per repair should be much cheaper.

TABLE 6.2

NETWORKED SYSTEM COMPARISON

NETWORK	COST	DETECTION EFFICIENCY	ACCURACY	FALSE ALARM RATE	COVERAGE	DETECTION
SUNYA		70%	Azimuth-Excellent	Low	CONUS	+/- Cloud-to-Ground
One time cost	$9,350 Hardware plus $200 shipping/sys $1,250 installation fee plus travel (includes training)		Range-depends on where you are with respect to the network. 2-5km center 10km edges			
Recurring	$7,000 Comm/yr*					
R-SCAN		35-45%	Azimuth-Excellent Range-Variable 1-20km depending on timing accuracy and effects of non-CG lightning and extraneous sources	Unknown but probably moderate	CONUS	All lightning and other electro-magnetic emissions
One time cost	$3,950 Hardware/sys** $ 595 Software					
Recurring cost	$ 125/mo Comm					
R-SCAN 960	$ 995/mo Access					
R-SCAN 480	$ 495/mo Access					
R-SCAN 240	$ 295/mo Access					

*Assumes a single user - multiple users would lower cost significantly.
**Assumes purchase of hardware - renting eliminates hardware cost but increases comm cost.

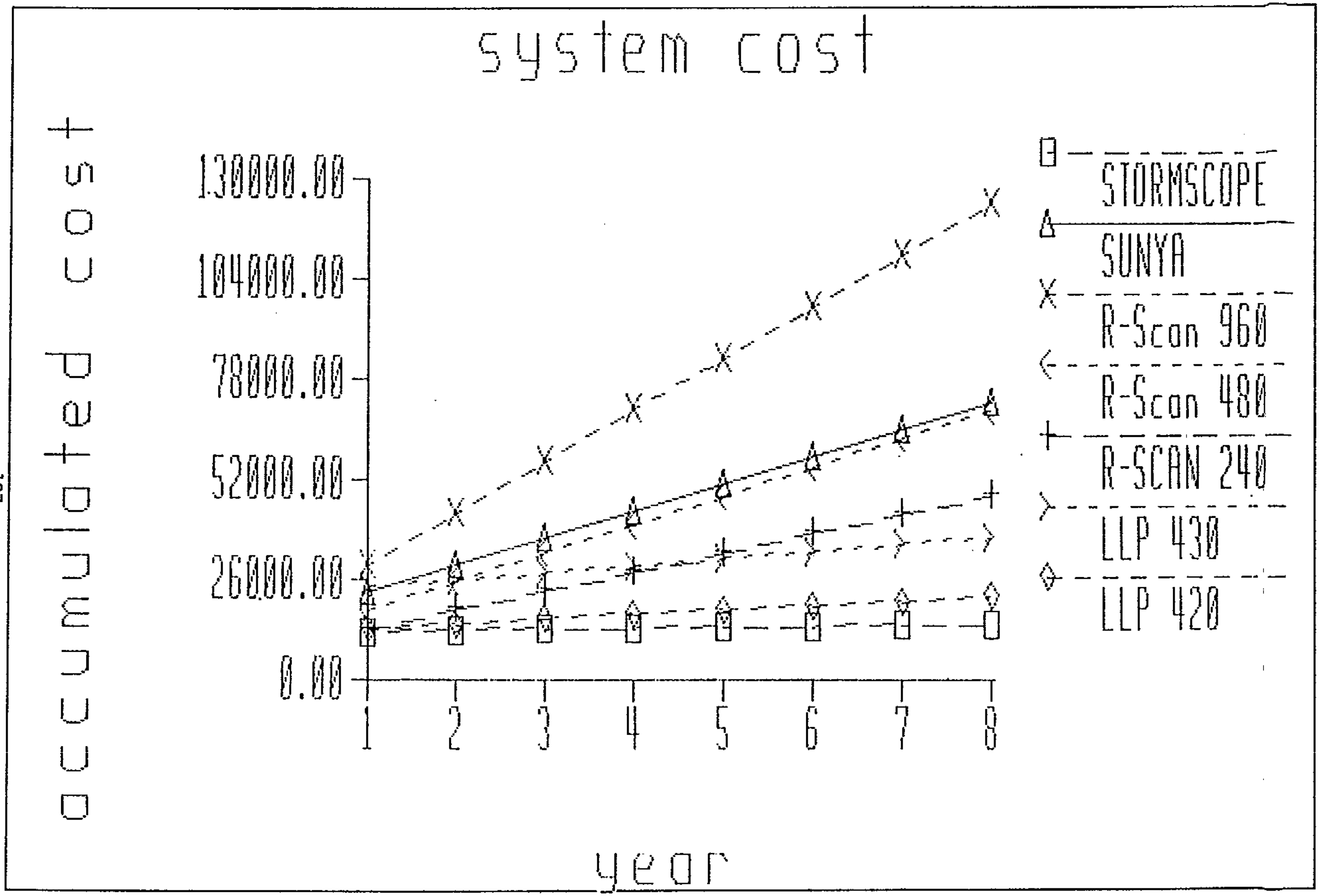


Figure 6-1. System cost projections.

7.0 CONCLUSION.

Lightning detection systems, networked on single point, offer an excellent means to supplement radar, satellite, and conventional data as an aid to locating areas of lightning occurrence. Only the lightning detector offers an unambiguous answer to the question, is there or is there not lightning associated with showers and convective build-ups. The systems are moving out of the research and development phase and into the realm of operational meteorology. Already numerous users employ the systems to protect various resources and operations which are sensitive to lightning strikes. Location accuracy, detector efficiency, and costs vary between currently marketed systems, so one must carefully research the systems available and the operational need before plunging ahead with an acquisition. However, once the appropriate homework is done to match cost, needs, and capabilities, a lightning detection system can provide increased protection to sensitive facilities and operations. In the final analysis, each staff weather officer must decide which system will best support the weather customer's operational requirements at least cost.

REFERENCES

1. The Key to Lightning Technology, 1984: International Aerospace and Ground Conference on Lightning and Static Electricity (Orlando), 393pp.

2. Carl C. Ewald, 1987: Operational Use of Cloud to Ground Lightning Strike Data at a Center Weather Service Unit (CWSU). NWS-ER-TA-87-11(A), 4pp.

3. B. D. Fisher and N. L. Crabill, 1987: Summary of Flight Tests of an Airborne Lightning Locator System and Comparison with Ground-Based Measurements of Precipitation and Turbulence. NASA Langley Research Center, 251-278 pp.

4. B. D. Fisher and J. A. Plummer, 1987: Managing Risks from Lightning Strikes to Aircraft. 14th Flight Safety Foundation Seminar on International Air Safety (Tokyo), 22pp.

5. Gregory G. Gerwitz, 1987: Operational Use of Real Time Lightning Data at a National Weather Service Forecast Office. NWS-ER-TA-87-11(B), 5pp.

6. W. A. Lyons and R. B. Bent, 1986, Operational Uses of Data from Several Lightning Position and Tracking (LPATS). R-SCAN, 10pp.

7. Waltor A. Lyons, 1987: Lightning Detection Network: Playing an Ever Increasing Role in Applied Research and Operations. R-SCAN, 1pp.

8. Technical Data Sheet, 1987: Lightning Location and Protection, Inc. (LLP) Model 420A. Lightning Location and Protection Inc., 6pp.

9. Technical Data Sheet 1988: 3M "Ryan" Stormscope WX-120. 3M Stormscope, 3pp.

10. Technical Data Sheet, 1988: The R-Scanner. R-Scan Corporation, 9pp.

11. M. W. Maier and W. Jafferis, 1985: Locating Rocket Triggered Lightning Using the LLP Lightning Locating System at the NASA Kennedy Space Center. 10th International Conference on Lightning and Static Electricity (Paris), 9pp.

12. Henry Newhouse, 1987: Lightning Detection Systems: A Status Report. National Weather Digest, p22-25.

13. R. E. Orville, R. W. Henderson, and L. F. Bosart, 1983: An East Coast Lightning Detection Network. Bull of Amer Met Soc, Vol 64, p1029-1037.

14. Edwin P. Weigel, 1976: Lightning: The Underrated Killer. NOAA Reprint, Vol 6, 6pp.

15. Characteristics of Lightning, 1986: Electrical Fields and Charge Separation (Part I) and The Discharge and its Relationship to Thunderstorm Characteristics (Part II). NWS-WR-TA-86-17 & 18, 5pp. and 8pp.

16. Preliminary National Plan for Lightning Detection Systems, 1988: Office of the Federal Coordinator for Meteorological Services and Supporting Research, 45pp.

17. The Status of National Programs for Lightning Detection Systems, 1986: Office of the Federal Coordinator for Meteorological Services and Supporting Research, 48pp.

18. D. R. MacGorman and W. D, Rust, 1988: An Evaluation of Two Lightning Ground Strike Locating Systems. NOAA Environmental Research Laboratories, 76pp.

19. Richard E. Orville, 1987: Meteorological Applications of Lightning Data. Reviews of Geophysics, Vol 25, No 3, p411-414.

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PROCEEDINGS OF

THE 3D LIGHTNING WARNING WORKSHOP

14 August 1992
University Park Hotel
Salt lake City, Utah

MISSING PAGE

194

Preliminary Announcement

3RD LIGHTNING WARNING WORKSHOP

Presented by the

Lightning Prediction and Detection Committee

of the

Range Commanders Council/Meteorology Group

at the

University Park Hotel, Salt Lake City, UT

Friday, August 14, 1992

8 AM-3 PM

This workshop is directed toward meteorologists and others who must provide lightning warnings to at-risk activities, and those who interpret and use lightning warning information.

SESSIONS

1. **Tutorials** (suggested topics)–[25-30 min. each plus 5 min. for Q&A]
    1) Thundercloud Electrification Process; Intracloud and Cloud-to-Ground Lightning Characteristics
    2) Measuring and Interpreting Cloud Electrification Data
    3) An Overview of Lightning Discharge Detection Techniques and Interpretation of Information

    Break [15 min.]

2. **Range Applications of Cloud Electrification and Lightning Detection Data and Information**

    [up to 8 presentations; 2 h total–10 min. each plus 5 min. for Q&A]

    Lunch [1 hour]

3. **Future Techniques for Obtaining, Interpreting, and/or Presenting Cloud Electrification and Lightning Detection Data and Information**–[up to 6 presentations; 2 h total–15 min. each plus 5 min. Q&A]

Charter And Objectives of the Lightning Prediction And Detection Committee (LPDC)

- Identify mutual problems, share knowledge and techniques, and serve as the focal point for issues associated with the prediction and detection of lightning.
- Suggest and/or recommend equipment and procedures that can:
    - Enhance safety
    - Reduce down time for "at-risk" activities.
    - Provide timely and credible information to duty weather forecasters.

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WHAT IS THE RANGE COMMANDERS COUNCIL/METEOROLOGY GROUP?

The Range Commanders Council (RCC) is a Department of Defense organization representing all of the national test ranges. Its primary purpose is to enhance the national capability for research, development, test, and evaluation at member ranges. A key function is to ensure uniformity in all aspects of range instrumentation and control throughout all of the member and associate member ranges—initially, the organization was referred to as the Inter-Range Instrumentation Group (IRIG). One RCC group, the Meteorology Group (MG), is concerned with bettering the capabilities of range geophysical agencies to define the effects of atmospheric and oceanic parameters on aeronautical, marine, missile, and space systems. The MG focuses its efforts on the instrumentation and techniques used to measure, predict, and evaluate these effects, and on improving overall environmental support to range activities and users.

HISTORY OF THE LIGHTNING WARNING WORKSHOP

In May, 1987, members of the RCC Meteorology and Range Safety groups were surveyed to determine their needs and concerns regarding lightning threat warning. One response that was essentially unanimous was an interest in having a workshop at which they could gain much needed information and discuss their particular problems. In response, the *Lightning Threat Warning Workshop* – sponsored by Lawrence Livermore National Laboratory—was held in Cocoa Beach, FL in September of 1987. An outgrowth of that workshop was the *Interagency Lightning Threat Warning Working Group.* Although several working group meetings were held, and two newsletters were published, this *ad hoc* group lacked a parent organization.

The RCC/MG's interest in forming a lightning committee resulted in the *Thunder and Lightning Seminar* being held in conjunction with their February, 1990, meeting in Las Cruces, NM. Subsequently, the executive council of the RCC authorized the formation the Lightning Prediction and Detection Committee (LPDC) as a part of the Meteorology Group.

The objectives of the aforementioned working group served as the basis for the LPDC charter, with one of those objectives being to periodically conduct lightning workshops. Since many of the attendees at the previous workshop and seminar were RCC members, we believe it is appropriate to identify the August 1992 workshop as the *3rd Lightning Warning Workshop.*

FRIDAY, 14 AUGUST 1992
3rd LIGHTNING WARNING WORKSHOP

0730	Registration	
0800	Convene/General Announcements	Mr. L. Corbett MR. R. Hasbrouck
0815 - 0945	<u>Tutorials</u>: (note: topics, not titles are shown)	
0815 - 0845	-Thunderstorm Electrification Process; Intracloud and Cloud-to-Ground Lightning Characteristics	Dr. D. MacGorman
0845 - 0915	-Measuring and Interpreting Cloud Electrification Data	Dr. D. Latham
0915 - 0945	-An Overview of Lightning Discharge Detection Techniques and Interpretation of Information	Dr. D. MacGorman
0945 - 1000	Break	
1000 - 1200	<u>Range Applications of Cloud Electrification and Lightning Detection Information</u>:	
1000 - 1020	Nevada Test Site	Mr. M. Fair
1020 - 1040	Dugway Proving Ground	Dr. E. Astling
1040 - 1100	Kennedy Space Center	Dr. J. Ernst
1100 - 1120	State of Utah	Ms. B. Graham
1120 - 1140	White Sands Missile Range	Mr. D. Thornley
1140 - 1200	Group Discussion of Other Applications	Workshop Chairman
1200 - 1300	Lunch	
1300 - 1430	<u>Future Techniques for Obtaining, Interpreting, and/or Presenting Cloud Electrification and Lightning Detection Information</u>:	
1300 - 1330	-Lightning - Rainfall Relationships in an Isolated Mid-Atlantic Thunderstorm	Mr. R. Kane
1330 - 1400	-Integration of Lightning and Radar Data to Complement Automated Surface Observations	Mr. A. Stern
1400 - 1430	-A Comparative of the Temporal Variability of Lightning Observations and GOES Satellite Imagery	Mr. P. Roohr
1430 - 1500	Session Wrap-up	Mr. R. Kren Mr. R. Hasbrouck

OUTLINE OF TUTORIALS

Thunderstorm Electrification Process; Intracloud and Cloud-to-ground Lightning Characteristics

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Measuring and Interpreting Cloud Electrification Data

An Overview of Lightning Discharge Detection Techniques and Interpretation of Information

---

Presented by

Dr. Don MacGorman

NOAA/National Severe Storm Laboratory

and

Dr. Donald Latham

USDA/Forest Service Research
Inter mountain Fire Sciences Laboratory

I. Thunderstorm electrification

A. Thunderstorms introduction

- involve rain, usually ice, lightning, and of course, thunder

B. Definitions

- Q is property that explains observed electromagnetic forces
- Electric field gives the force that a test particle will feel
- Will use sign convention that positive charge will move upward in a positive vertical electric field in the atmosphere

C. Grossly simplified charge structure

- thunderstorm dipole: positive charge over negative

D. Brief summary of charging mechanisms

- microphysical separation by inductive and non-inductive mechanisms
- currents to cloud boundaries
- charge transport by sedimentation and convection

E. Growth of electrification

- observations of rapid growth to electrification and of increase in electrification with increasing mid-level radar reflectivity and updraft above -20°C isotherm

F. Differences in different types of storms

- Gulf Coast (e.g., Florida), continental, and tropical (CG fraction, dBZ vs. lightning, height vs. lightning) and winter vs. summer multicell or single cell vs. supercell

G. Brief introduction to numerical storm models that include electrification

II. Detecting electrification of clouds

A. Direct measurements by balloons, aircraft, and rocket

B. Indirect measurement and the Poisson's Law dilemma

- Charge models necessary
- equations determine the minimum number of necessary field measurements
- Field mill arrays as charge distribution probes

C. Radar as backup for field mill (or field change meter) arrays

D. Radar polarization (new stuff) to determine electric field in clouds

E. Possible use of mesoscale models to help determine growth

III. Characteristics of Intracloud and Cloud-to-Ground Lightning

A. General remarks concerning types of lightning and nomenclature

B. Non-existence of "sheet", "heat", "bead" lightning as separate phenomena

C. Intracloud discharges

- in-cloud, cloud-to-cloud, and "air" discharges

D. Cloud-to-ground discharges

- Types: positive, negative, up-going, down-going (and what direction means)
- CG processes: 1st leader, return stroke, between-stroke processes, dart leader, subsequent return stroke, etc.
- radiation from lightning discharges
  - acoustic
  - light: strong lines such as h-alpha
  - radio-frequency radiation: low frequencies from "long" events, vhf frequencies from branching processes in cloud

- separation of discharge types by radiation signatures

IV. Lightning mapping systems

A. Can map lightning from almost any form of radiation that is distinguishable from cloud environment - acoustic, radio, optical - as well as by radar and delta E. Concentrate on techniques that use electromagnetic radiation, such as radio

B. LLP

- summary of technique, error sources

C. LPATS

(ditto)

D. Interferometer - 2d and 3d

- summary of technique, list of present systems, error sources

E. TOA

- summary of technique and brief mention of systems that have used it

F. Satellite

- very brief summary of technique and target date of availability

G. Lightning mapping data interpretation

- convective tendency, rainfall trends, cg:total lightning vs. storm stage, +CG modes and seasonal trend (winter, end-of-storm, stratiform/anvil, severe storm)

V. Decision-making aspects of lightning information

A. Combining data and use of GIS displays

- satellite, radar, electric field, lightning location, local forecaster skill

B. Range protocol and directives

- What's at risk?

- What's the cost?

- Agreeing?

C. Tools

- Expert systems for codification and decision steering

- ROC analysis, operating point

A COMPARATIVE ANALYSIS OF THE TEMPORAL VARIABILITY OF LIGHTNING OBSERVATIONS AND GOES IMAGERY

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ABSTRACT

Lightning Positioning and Tracking System (LPATS) data received by CIRA via a real-time weather data network was used to study the temporal variability of lightning for a frontal system and hurricane which affected the U.S. in 1989 (1). Our comparison of this data with GOES-7 imagery revealed that lightning data can help define the development, linearity, and maximum intensity of a frontal band as seen with the correlation of currents discharged by lightning to ground with associated IR temperature fields. Lightning data also revealed a dramatic increase in convection equatorward of Hurricane Chantal's vortex upon her rapid intensification and landfall, and the heavy rainfall amounts associated with the tropical storm correlated to areas of rather frequent lightning activity west of Galveston, Texas on August 1, 1989.

INTRODUCTION

The fitting of thunderstorms and lightning into the global circuit and the correlation of lightning to the radar characteristics and cloud features of varied convection has been the focus of research for many years. Over the last two decades advances in electronics, the discovery of a correlation between the location of a lightning strike to ground and the peak in the return-stroke waveform, and the elimination of intracloud flashes due to their frequency characteristics led to the development of lightning detection via magnetic direction-finders (MDF) and time-of-arrival (TOA) systems. Bent and Lyons (2) developed a system for the location of cloud-to-ground (CG) lightning activity utilizing the TOA radio frequency technique; their LPATS design became the cornerstone for a highly accurate nationwide lightning detection network in the late 1980's. With CIRA's access to this LPATS data and development of a user friendly lightning display and archival system (3) research into the characteristics of CG lightning associated with a mature cold front and an intensifying tropical storm became possible.

The objectives of this paper include: The review of past work correlating CG lightning with GOES imagery and/or radar data; the evaluation of the temporal characteristics of CG lightning strokes that are discharged by two distinct weather systems; and the definition of the results of the analysis in such a way that both the researcher and forecaster can better understand the complicated processes of varied convection.

FUSION OF LIGHTNING, RADAR, AND/OR SATELLITE DATA FOR SCIENTIFIC PURPOSES

Many meteorologists over the past 15 years have studied the temporal and spatial variability of synoptic/mesoscale patterns with a combination of satellite, radar and/or CG lightning data; they studied lightning activity not only for the sake of analysis but also to attain a better understanding of how thunderstorms sustain the "ionospheric potential" that exists between the negatively charged surface of the earth and the positively charged atmosphere. Orville *et al* (4) presented the first simultaneous display of lightning ground strike locations overlaid on visible and infrared satellite images; the displays verified that the lightning locations tended to overlay the coldest cloud tops and that these locations occupied a small fraction of the total cloud cover over Oklahoma for a large storm system. Orville *et al* (5) observed that lightning activity (picked up by the SUNYA MDF network) associated with an unusually severe convective line moving southeastward over New England provided the first important indications of cyclone intensification and associated heavy precipitation that two models (limited fine mesh (LFM) and nested grid (NGM)) and satellite data could not detect or forecast by themselves. Edman (6) used LPATS data received by the National Severe Storms Forecast Center (NSSFC) in combination with radar and satellite data to study two convective outbreaks over southern Minnesota, and one over Iowa; TOA technology showed its promise here by depicting the temporal variability of thunderstorm updraft regions.

Goodman and MacGorman (7) utilized enhanced GOES IR satellite data in combination with lightning data picked up by the National Severe Storms Laboratory (NSSL) detection network to study relationships between CG strokes and the areal spread of certain cloud top temperatures of Mesoscale Convective Complexes (MCCs). Rutledge and MacGorman (8) examined the 10-11 June 1985 Kansas squall line observed during the O-K PRE-STORM Project; using the NSSL lightning detection network, two NCAR Doppler radars and one NWS WSR-57 radar they studied the location and polarity of the CG lightning flashes relative to the radar echo structure of the storm. Correlations were found between the peak convective rainfall amount and the peak negative CG flash rate as well as between the peak stratiform rainfall amount and the peak positive CG flash rate. Rutledge *et al* (9) presented more extensive observations of CG lightning and radar reflectivity patterns in Mesoscale Convective Systems. Goodman *et al* (10) developed a technique that will generate convective tendency products by combining GOES satellite imagery with observations of CG lightning activity. A few examples of these generated products illustrated how the flash rate trend might produce a much different and more useful portrayal of storm evolution than the time rate of change of cloud-top blackbody temperatures.

On a climatological basis Reap and MacGorman (11) found a good correspondence between lightning frequency and radar echo intensity within the effective range of the Oklahoma City WSR-57 radar (for the 1985-86 warm seasons). Both positive and negative flashes were found to be strongly correlated with the low-level moisture flux and circulation; contrary to expectations, freezing level and wind shear were not nearly as important as the boundary fields in determining thunderstorm formation and subsequent positive CG lightning activity. Reap (12) compared a collection of two million CG lightning strike locations for the 1983-84 summer seasons over the western U.S. with manually digitized radar (MDR) data and GOES-West satellite observations from the Techniques Development Laboratory's (TDL) data archives. Reap found that 87% of the strikes occurred with radar intensity levels less than VIP3, the threshold normally used for delineating thunderstorms in the eastern U.S..

Lightning data has also been compared with satellite imagery and radar data for tornadic activity and hurricanes. MacGorman *et al* (13) acquired NSSL lightning and Doppler radar data on two tornadic storms in Oklahoma on 22 May 1981; in both storms, there was no clear relationship between tornado occurrence and ground flash rates of the storm as a whole, but the stroke rate of each storm was highest after it stopped producing tornadoes. Lyons *et al* (14) examined Hurricane Florence with LPATS data and GOES imagery; GOES imagery revealed a massive supercell which had exploded near the center of the storm in association with a burst of lightning activity in the southwest quadrant of the storm.

The results of the past work mentioned above helped provide a direction for the work accomplished in this paper. Access to GOES-7 satellite data and LPATS lightning data enabled an analysis of the ability of each data set to help a forecaster predict the development, intensification, and dissipation of certain convective regimes.

CASE STUDY #1: COLD FRONT

SYNOPTIC OVERVIEW - The first case study involves the rapid frontogenesis which took place over the eastern third of the United States on November 15, 1989. Very much a spring type synoptic system it was responsible for 21 deaths and many injuries in Huntsville, Alabama as well as a few casualties in New York state. Two areas of positive vorticity advection were evident on the 15/1200Z NGM analysis over Iowa, Illinois and Missouri; at the surface a very cold packet of air from western Canada reinforced a developing cold front situated over the Great Plains during the morning hours of 15 Nov; the cold air clashed with very most air coming off of the Gulf of Mexico creating a battle line of convection which left many locations in the southeastern U.S. with a lot of rain (1-2" in 6-10 hrs) and some with damage from lightning and tornadic activity. Figure 1 depicts two GOES Visible satellite shots of the large system at 15/1400Z and 15/2100Z; the former satellite image depicts a disorganized frontal system over the central United States with convective activity located mainly north of the Mason-Dixon line while the latter image depicts a better organized front with strong activity over the cotton belt. Radar summaries depicted thunderstorm tops exceeding 37,000 ft north of Tennessee at

1415Z; the same data source showed thunderstorm tops exceeding 46,000 ft at 2130Z (with numerous reports of hail and TRW+ south of Tennessee).

ANALYSIS OF LIGHTNING ACTIVITY ALONG FRONT - With the multitude of lightning strokes over the midwestern U.S. on 15 Nov the data was divided into half-hour increments (Figure 2) to achieve the resolution of certain cells along the front. The CIRA lightning display depicts both positive and negative cloud to ground lightning strikes via simple geometry (i.e., negative CG strikes have negative slope while positive strikes have positive slope). The varied lengths of the lightning strikes correspond to the varied current lowered to ground by the strikes; the smallest current depicted in Figure 2 is LTE 1 kiloamp while the largest current is GTE 75 kiloamps. The top half of the figure shows lightning activity from 1330 to 1400Z and 1430 to 1500Z while the bottom half shows activity from 2100 to 2200Z.

From 1230 to 1530Z the large area of lightning in central Illinois at first took on a concave shape with a decrease in CG activity at its southern periphery; a noticeable split in the rather intense activity showed up in the 1300 to 1400Z increment. The eastern half of the split group grew in areal coverage as it moved into Indiana and then attained a concave shape (opposite to that mentioned *a priori*). The western half of the group decreased in areal coverage and its percentage of positive CG discharges increased; at this time cold air from the surface to near the 700 mb level had been spreading over most of Illinois and northern Indiana. The currents associated with the eastern group of negative CG lightning activity increased to near 50 kAmp; the positive CG strokes of the western group lowered 250 to 350 kAmp. The line in northern Indiana broke up into four obscure packets which decreased in size, and a very large area of strong negative discharges in Ohio grew and then died within the 1329 to 1459Z time frame. Three areas of well defined strong negative CG lighning activity appeared in southern Illinois by 1500-1529Z time frame while cells of weak CG strikes developed in southern Missouri, central Arkansas and eastern Texas.

From 1830 to 2130 GMT activity along the southern Mississippi River valley increased as the sporadic area of lightning in northern Mississippi organized itself into two lines; very well defined lines of 1 kAmp negative CG discharges initially showed up in eastern Arkansas and Louisiana. The V-shaped area of lightning in Louisiana (strongly indicating a squall line ahead of the surface front) broke up into smaller areas of activity and then reorganized itself into a moderately dense and wide line that stretched from Jackson, MS to southeast of Houston, TX. By 2130Z two more lines of lightning, one entering Alabama from the northwest and another in central Mississippi (which consisted of two defined cells) took shape and aligned themselves parallel to the line farthest south. The line over Indiana moved east into Ohio while the cell from Kentucky merged with the line that had initially decreased in width; eventually this line regained its organization and intensified by the end of the period.

CORRELATION OF GOES IR IMAGERY TO LPATS DATA - To develop indices correlating IR pixel intensities to CG lightning stroke densities for many convective systems would greatly help the forecaster in his/her effort to forecast severe weather accurately and quickly; lightning data needs to be cross correlated with both radar and satellite data in order to be an effective forecast tool. Overall, the high correlation of high lightning frequency with cold IR cloud tops is well understood and accepted; this situation relates to a very developed charge separation and correlated strong electric fields in developed convetive regimes. The correlation of high/low lightning frequency to relatively warm IR cloud tops has been a subject of controversy for many years. It is hypothesized that strong wind shear behind the cold front (in this study) displaced charges horizontally enhancing the chances of positive discharges to ground (tilted dipole effect); the lowering of the freezing level behind the front also could have enhanced the positive CG lightning activity as supercooled water droplets in the thick nimbostratus and weak convective cloud decks would have increased the positive charge closer to ground level. The correlation of low CG lightning activity with cold IR cloud top regions indicates that are times when areas of lightning generation in thunderstorms will be too high to such an extent that CG activity will be minimal.

An hour by hour analysis of the correspondence between lightning frequency (and stroke current) and IR cloud top temperatures helped to distinguish certain stages of frontal development. Figure 3a displays graphs of CG lightning stroke current versus IR pixel intensity for certain 5 minute increments of the frontal system's life (specifically 1430 to 1435Z and 2130 to 2135Z). Figure 3b represents an examination of the number of CG lightning strokes per specific IR pixel intensity values for certain 5 minute increments of the system (specifically 1330 to 1335Z and 2230 to 2235Z).

The 1430-1435Z graph depicts the disorganization of the lightning activity as some rather strong negative CG discharges existed under cloud tops with temperatures of 271K as well as 220K (Table 1 in back relates IR pixel intensity to cloud top temperature). Most of the negative CG discharges lowered 20 to 45 kAmps to the surface; the positive discharges were not as frequent but were definitely stronger (most in 50 to 150 kAmp range). The number of negative CG discharges with smaller amplitude correlates to the development of the front's southern periphery. Lightning activity during the 2130-2135Z time frame illustrated the most active and mature stage of the front as the number of very strong positive CG discharges reached a maximum and the number of moderately strong negative CG discharges began to decrease. The evidence of weaker strokes (positive and negative) under IR pixels with intensities between 110 and 160 seemed to depict the existence of electrical activity under thick stratocumulus (Sc) and Nimbostratus (Ns) clouds behind the convective areas of the front and also associated squall lines; radar data at 2135Z and 2235Z showed that the lightning activity was actually occurring under Sc and Ns clouds with embedded strong rainshowers.

During the earlier stages of the frontal system (0930-1230Z) the highest frequency of CG strokes did not correlate to the coldest IR temperatures (showing disorganization and development of front in general). The 1330-1335 graph shows this feature also but two peaks of activity exist, one in the 215K cloud top range and the other in the 230K range; the 230K peak corresponded to the development of the convection on the southern flank of the cold front while the 215K peak correlated to the well established northern part of the front where most lightning strokes (positive as well as negative) occurred under very cold cloud tops. During the most active moments of the system (as shown in the 2230-2235Z graph) the highest number of strokes occurred under cloud tops with about a 214-216K temperature (this number approaches stayed above 60 strokes (per 5 minute period) from 2105 to 2205Z).

The importance of the aforementioned index analysis will be of great importance to the forecaster, but many questions arise: Can indices for other types of storm systems be developed and show the same promise? Will the indices help in the confusion connected with the time constrained analysis of data leading up to a forecast? Questions like these will be answered through further research and application. Overall, indices matching IR pixel intensities to CG lightning activity can and will help the typical forecaster predict the onset of lightning associated with a cold front which can threaten life and property.

CASE STUDY #2: HURRICANE CHANTAL

HURRICANE EVOLUTION AND EFFECT ON U.S. - In the early hours of July 30, 1989 a tropical depression formed in the south central Gulf of Mexico just north of the Yucatan Peninsula. The depression quickly developed into a tropical storm (named Chantal by the National Hurricane Center (NHC)) and then into the first Atlantic hurricane of the season by 4 PM CDT on the 31st of July. The hurricane continued its northwestward track during the evening and nighttime hours of the last day of July and made landfall at 7 AM CDT (Aug. 1) on the very northeastern fringes of Galveston Bay, Texas (Figure 4a); the intense thunderstorm activity on the southern side of the storm is not readily discernible on either visible or IR GOES imagery.

The storm continued to track northwest during August 1st passing north of Houston and near College Station by sunset; on this path it was downgraded to tropical storm strength by 0845 CDT and to a tropical depression by 1900 CDT (Figure 4b shows the storm at 1630Z when very heavy rain was hitting the Houston area). Hurricane forecasters categorized the strength of the storm as 1 on the Saffir-Simpson scale based on the fact that winds upon landfall reached 80 to 90 MPH. The main concern about the storm were the effects from the flooding produced by the very heavy torrential rains that fell to the west of where the hurricane made landfall (Figure 5); 10 to 12 inches of rain fell from northern Galveston west and northwest to central Ford Bend County.

ANALYSIS OF CHANTAL'S CG LIGHTNING ACTIVITY - Although lightning caused no fatalities during the life of the storm (drowning related to all 13 deaths) its movement, areal extent, and intensification could be used to help the NHC forecast the time of landfall along with regions of associated heavy precipitation; important convective regions of hurricanes can be monitored with the aid of CG lightning location systems.

Figure 6 portrays the lightning activity of Chantal from both 1200-1259Z and from 1600-1659Z. The 1200-1259Z protion of the figure illustrates the dramatic intensity of CG lightning activity on the equatorward side of the storm upon Chantal's landfall in SE

Texas. In a previous study Johnson and Goodman (15) recorded an increase in equatorward (of the vortex) lightning activity for Hurricane Alicia as the storm made landfall (also the Texas coastline). CG lightning activity as observed in the 1600-1659Z time slot correlates very well to the area of heaviest rainfall south and west of Galveston, TX (compare Figures 5 and 6).

Figure 7 illustrates lightning activity on the equatorward side of the storm as well as the lightning activity for the storm as a whole. The peak of activity at about 1200Z directly correlates to the landfall of the storm while the smaller peaks of storm CG strokes at 1600 and 1800Z correlates to the time of heaviest precipitation (located northeast of storm track).

GOES IMAGERY VERSUS LPATS DATA FOR STORM - Lightning data clearly enhances a forecaster's ability to correctly indicate the timing of intensification for a major hurricane as it makes landfall; something he/she cannot do with just satellite data (as shown when examining Figure 4 and then Figures 4 and 6 combined). The LPATS data also improves the almost precise location of heaviest rainfall after hurricane landfall; this is vital when radar data is not available and flooding is a possibility. The IR (as well as radar) data at the time of Chantal's landfall indicates high cloud tops northeast and southwest of Galveston; lightning data helps to pinpoint the actual area of heavy precipitation under these high cloud tops.

CONCLUSION

Major findings of this paper include: **(a)** Lightning illustrated the linearity of convection in various degrees for the life of a major frontal system (the width and definition of squall lines appeared very well on the lightning display used at CIRA); **(b)** Plots matching CG lightning stroke currents and GOES IR imagery pixel intensities aided in the understanding of the development and intensity of a frontal system. Not all CG lightning strokes occurred under the coldest cloud tops as some (mostly negative) tended to hug the leading edge of relatively warmer cloud top fields and associated radar reflectivity zones; lightning under warmer cloud top fields on the southern flank of the front corresponded to the development of convection and charge separation in that region. Behind the front a rather high percentage (15-35% depending on frontal development) of positive CG strokes existed under much warmer cloud top areas (associated with weak TRW and stratiform rain); **(c)** Lightning activity depicted the landfall of a major hurricane's northern spiral band, the explosion of convection equatorward of the storm's vortex just before and upon landfall, and the location of the most intense rain bands after landfall.

The potential for satellite and lightning data to improve the life of a forecaster is high. As technology enhances the capability of computers to display, relay and archive products that portray the overlaying of lightning data onto satellite data research associated with this paper will expand. Tentative plans for future research include: (a) An in depth analysis of lightning data collected in various countries to help redefine the climatology of convection on a global scale; (b) the creation of indices matching CG lightning stroke current and frequency to GOES IR pixel intensities for not only the lives of frontal systems but also for the lives of other weather systems such as snow squalls, mesoscale convective complexes, etc.

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REFERENCES

[1] Roohr, P.B., 1991: "A Comparative Analysis of the Temporal Variability of Lightning Observations and GOES Imagery", Master of Science Thesis, Colorado State University, Fort Collins, CO, 234 pp.

[2] Bent, R.B., and W.A. Lyons, 1984: "Theoretical Evaluations and Initial Operational Experiences of LPATS (Lightning Positioning and Tracking System) to Monitor Lightning Strikes Using a Time-of-Arrival (TOA) Technique", *Preprints, 7th Int'l Conf. on Atmospheric Electricity*, 3-8 Jun., Albany, NY, (AMS), 317-324.

[3] Whitcomb, D., D. Randel, S. Naqvi, and T.H. Vonder Haar, 1990: "A Real-Time Data Collection and Display Workstation", *Preprints, 6th Int'l Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*,7-9 Feb., Anaheim, CA (AMS).

[4] Orville, R.E., M.W. Maier, F.R. Mosher, D.P. Wylie, and W.D. Rust, 1982: "The Simultaneous Display in a Severe Storm of Lightning Ground Strike Locations onto Satellite Images and Radar Reflectivity Patterns", *Preprints, 12th Conf. on Severe Local Storms*, 12-15 Jan., San Antonio, TX (AMS), 448-451.

[5] Orville, R.E., R.W. Henderson, and L.F. Bosart, 1983: "An East Coast Lightning Detection Network", *Bull. Amer. Meteor. Soc.*, **64**, 1029-1037.

[6] Edman, D.A., 1986: "Operational Use of Lightning Location Information on an Interactive System", *Preprints, 11th Conf. on Weather Forecasting and Analysis*, 17-20 Jun., Kansas City, MO (AMS).

[7] Goodman, S.J., and D.R. MacGorman, 1986: "Cloud-to-Ground Lightning Activity in Mesoscale Convective Complexes", *Mon. Wea. Rev.*, **114**, 2320-2328.

[8] Rutledge, S.A., and D.R. MacGorman, 1988: "Cloud-to-Ground Lightning Activity in the 10-11 June 1985 Mesoscale Convective System Observed during the Oklahoma-Kansas PRE-STORM Project", *Mon. Wea. Rev.*, **116**, 1393-1408.

[9] Rutledge, S.A., C. Lu, and D.R. MacGorman, 1990: "Positive Cloud-to-Ground Lightning in Mesoscale Convective Systems", *J. Atmos. Sci.*, **47**, 2085-2100.

[10] Goodman, S.J., D.E. Buechler, and P.J. Meyer, 1988: "Convective Tendency Images Derived from a Combination of Lightning and Satellite Data", *Weather and Forecasting*, **3**, 173-188.

[11] Reap, R.M., and D.R. MacGorman, 1989: "Cloud-to-Ground Lightning: Climatological Characteristics and Relationships to Model Fields, Radar Observations, and Severe Local Storms", *Mon. Wea. Rev.*, **117**, 518-535.

[12] Reap, R.M., 1986: "Evaluation of Cloud-to-Ground Lightning Data from the Western United States for the 1983-1984 Summer Seasons", *J. Climate Appl. Meteor.*, **25**, 785-799.

[13] MacGorman, D.R., D.W. Burgess, V. Mazur, W.D. Rust, W.L. Taylor, and B.C. Johnson, 1989: "Lightning Rates Relative to Tornadic Storm Evolution on 22 May 1981", *J. Atmos. Sci.*, **46**, 221-250.

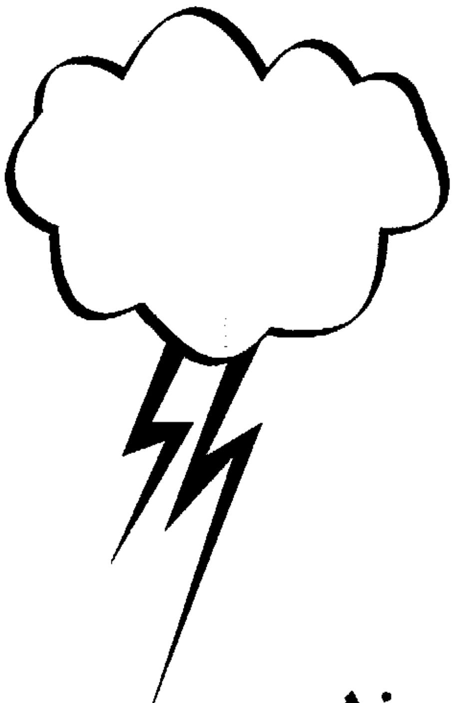
[14] Lyons, W.A., M.G. Venne, P.G. Black, and R.C. Gentry, 1989: "Hurricane Lightning: A New Diagnostic Tool for Tropical Storm Forecasting", *Preprints, 18th Conf. on Hurricanes and Tropical Meteorology*, 16-19 May, San Diego, CA (AMS).

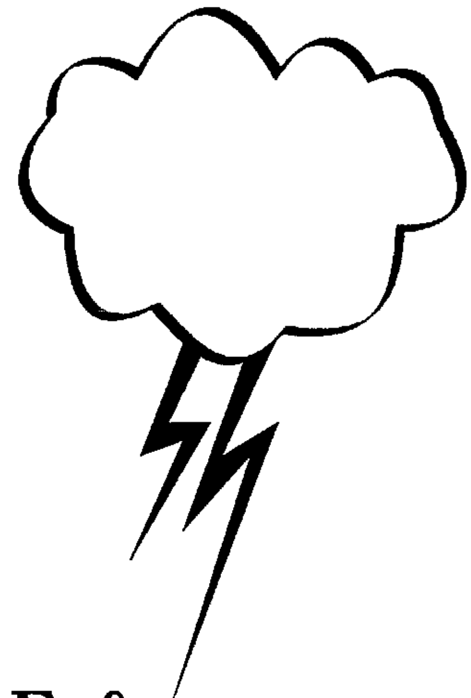
[15] Johnson, R.L., and S.J. Goodman, 1984: "Atmospheric Electrical Activity Associated with Hurricane Alicia", *Preprints, 7th Int'l Conf. on Atmospheric Electricity*, 3-8 Jun., Albany, NY (AMS), 295-298.

[16] Fujita, T.T., and D.J. Stiegler, Eds., 1989: "Outstanding Storms of the Month: 2. Hurricane Chantal, July 30 to August 3, 1989", *Storm Data*, **31**, 7-8.

[Please note: figures referred to in P.B. Roohr's paper were not submitted by author.]

A Comparative Analysis of the Temporal Variability of Lightning Observations and GOES Imagery





Capt Peter B. Roohr
Air Weather Service, USAF &
Cooperative Institute for Research in the Atmosphere,
Fort Collins, Colorado

Overview

- Past Studies
- Data Used for Case Studies
- Case Study #1: Cold Front
- Case Study #2: Hurricane Chantal

Past Studies

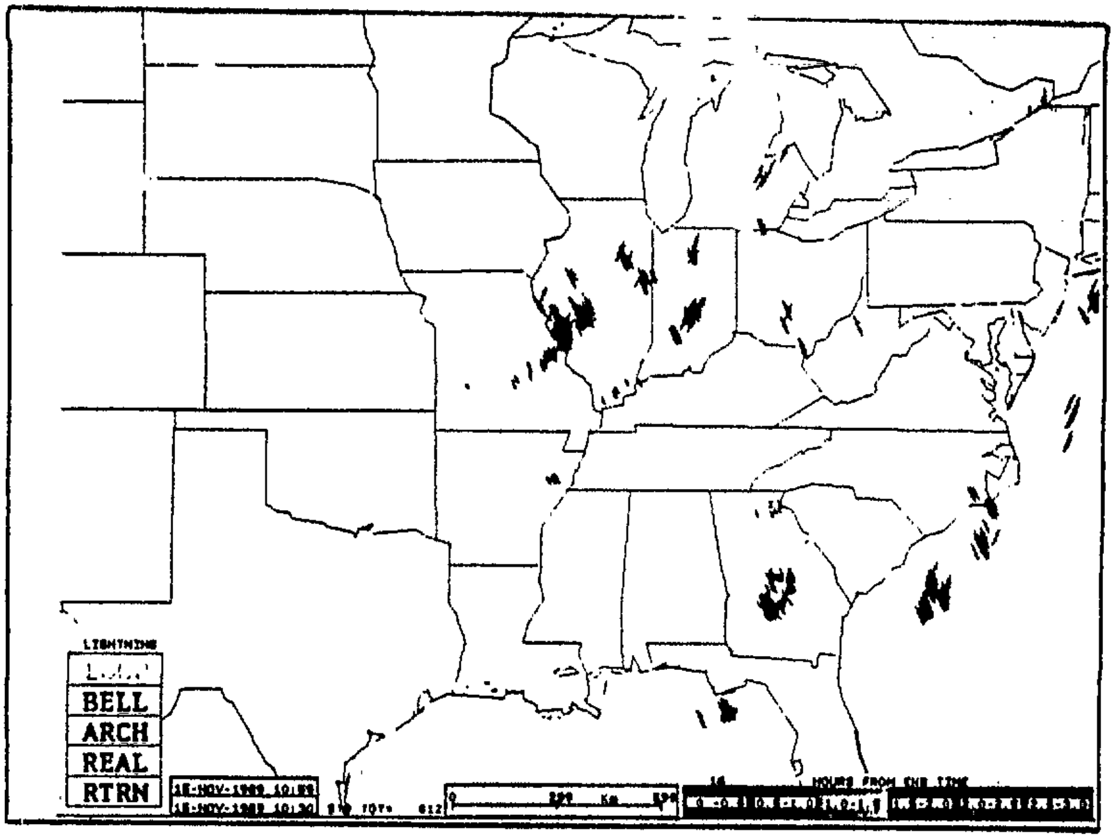
- Using LLP Sensors
  - Convective Activity
  - Mesoscale Convective Complexes
  - Tornadic Activity
  - Climatology
- Using LPATS Sensors
  - Convective Activity
  - Hurricanes

Data Used for Case Studies

- Time Interval
  - July to November 1989
- Area Interval
  - Central United States
- Sources
  - GOES-7
  - R*SCAN LPATS Network

Case Study #1: Cold Front

- Synoptic Overview
  - Surface Analysis
  - Upper Air Situation
- Analysis of CG Lightning Activity
  - Stages of Frontal Life
  - Compared to Radar Data
- Correlation of GOES Imagery to LPATS Data
  - CG Lightning Strokes vs IR Pixel Intensity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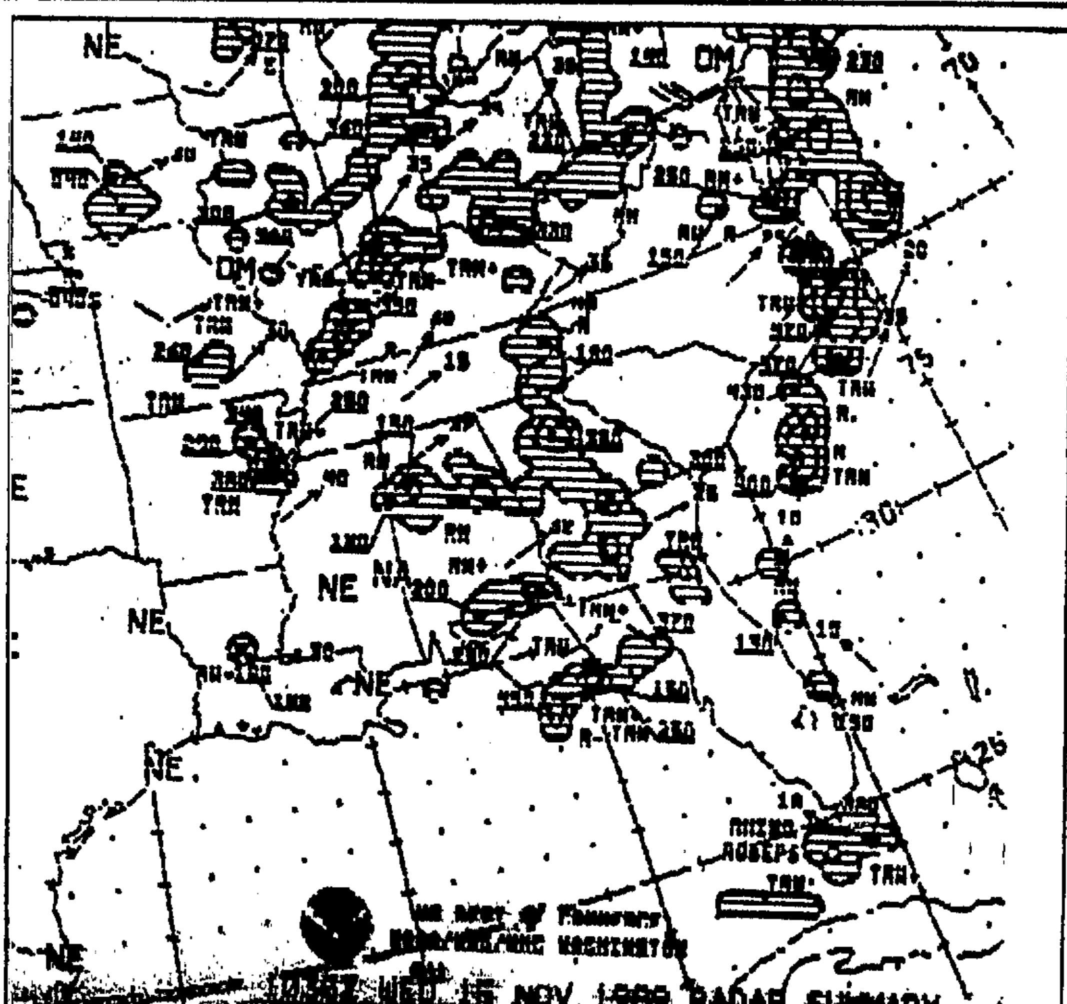
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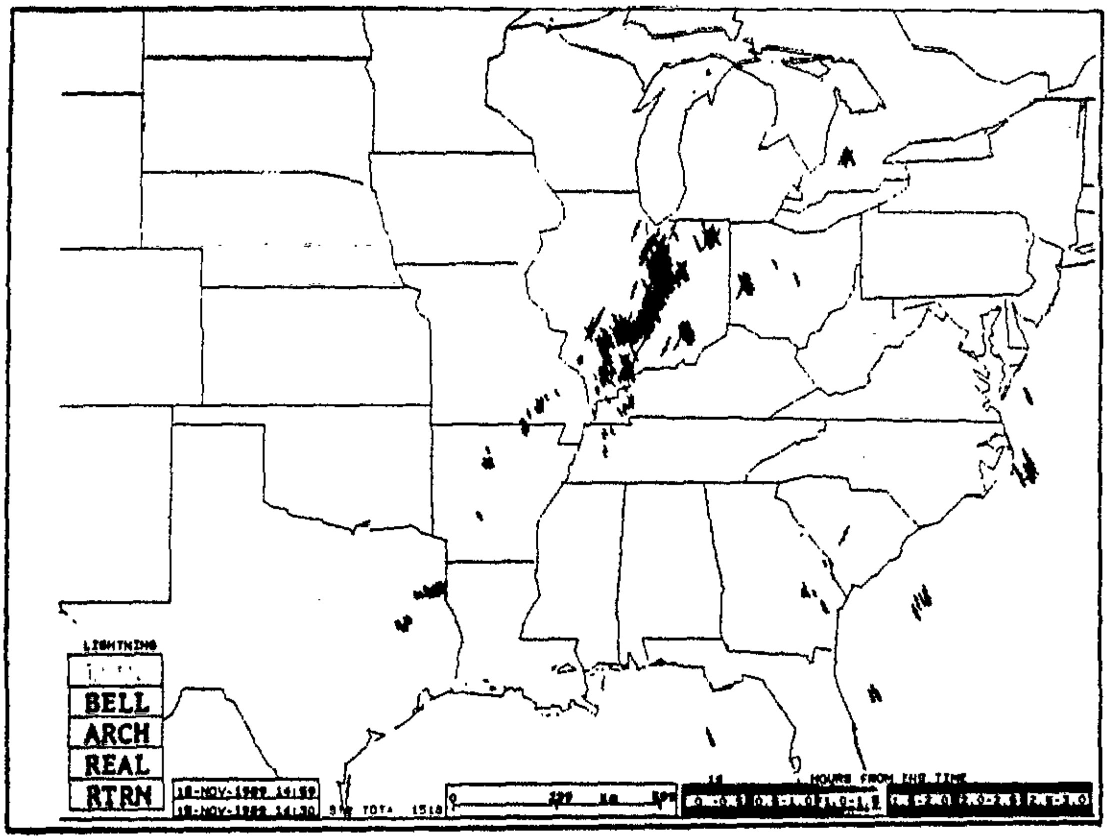
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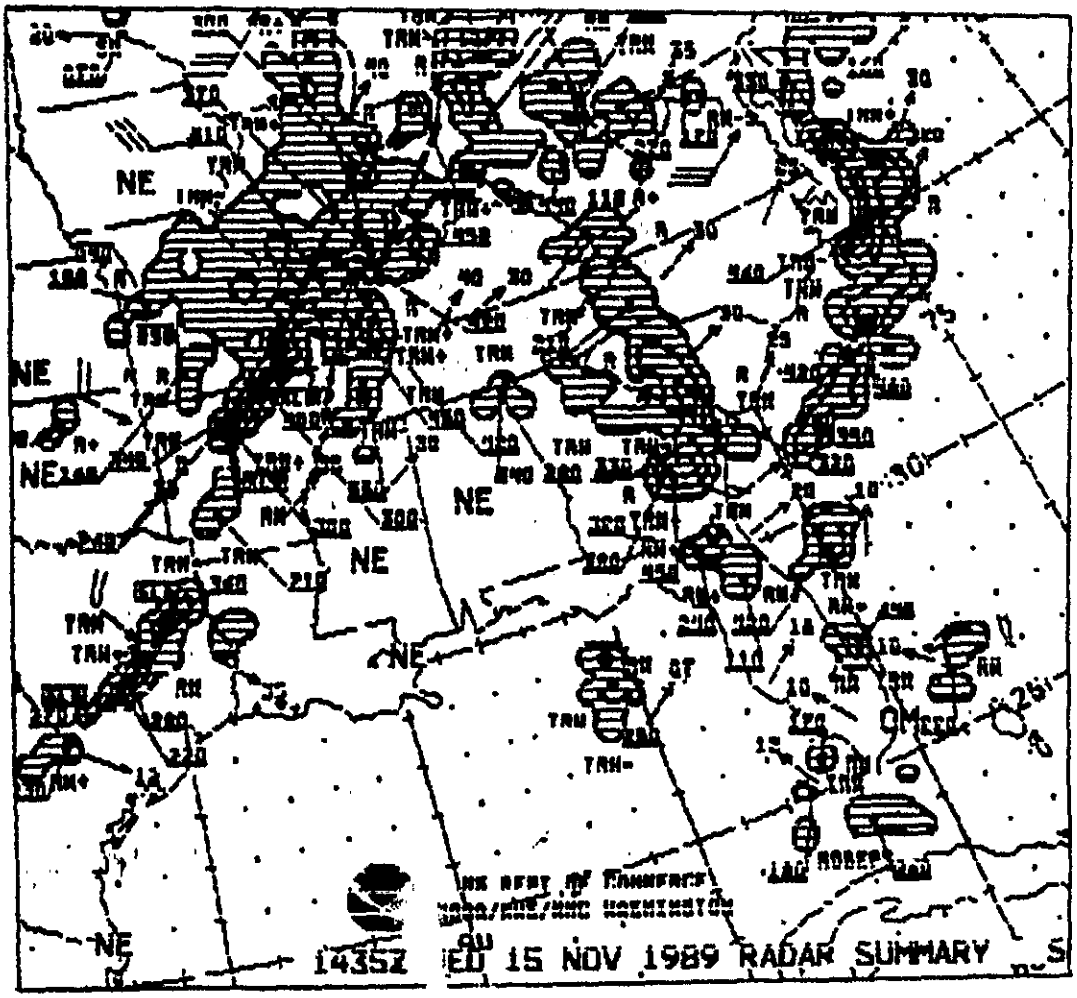
HOURS FROM END TIME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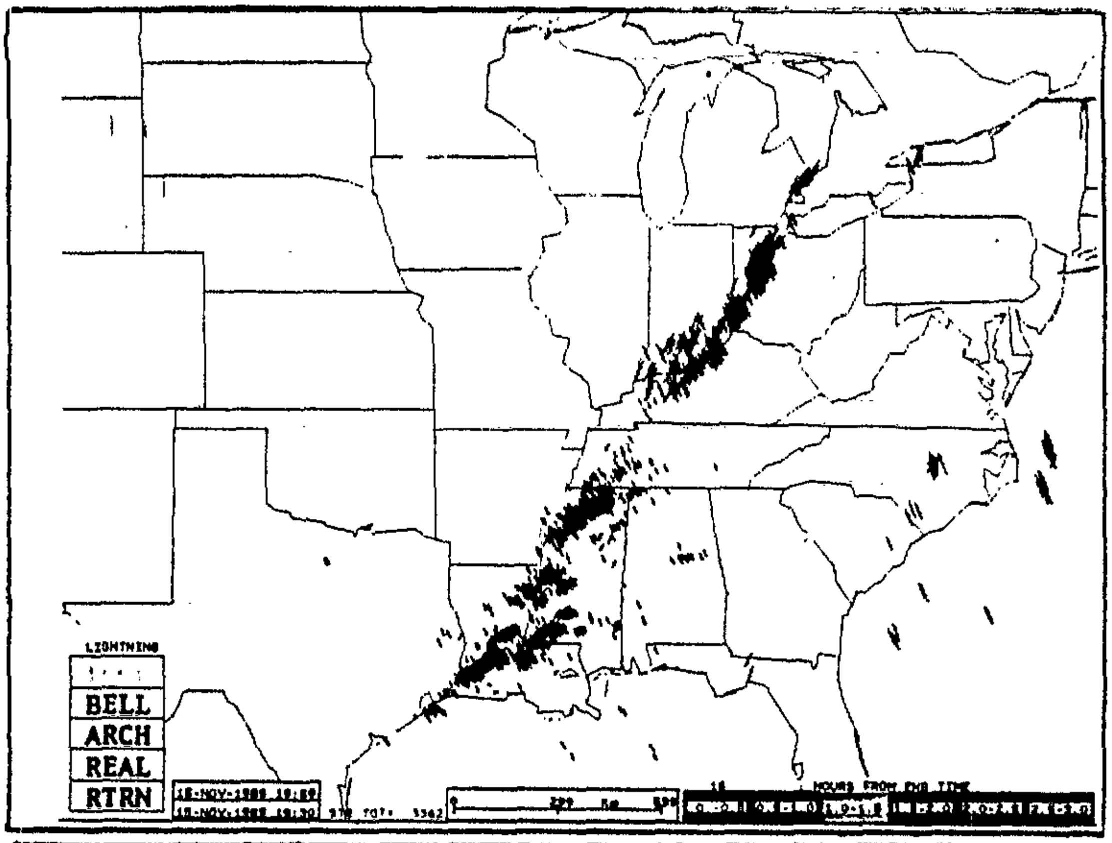
15 NOV 1989 RADAR SUMMARY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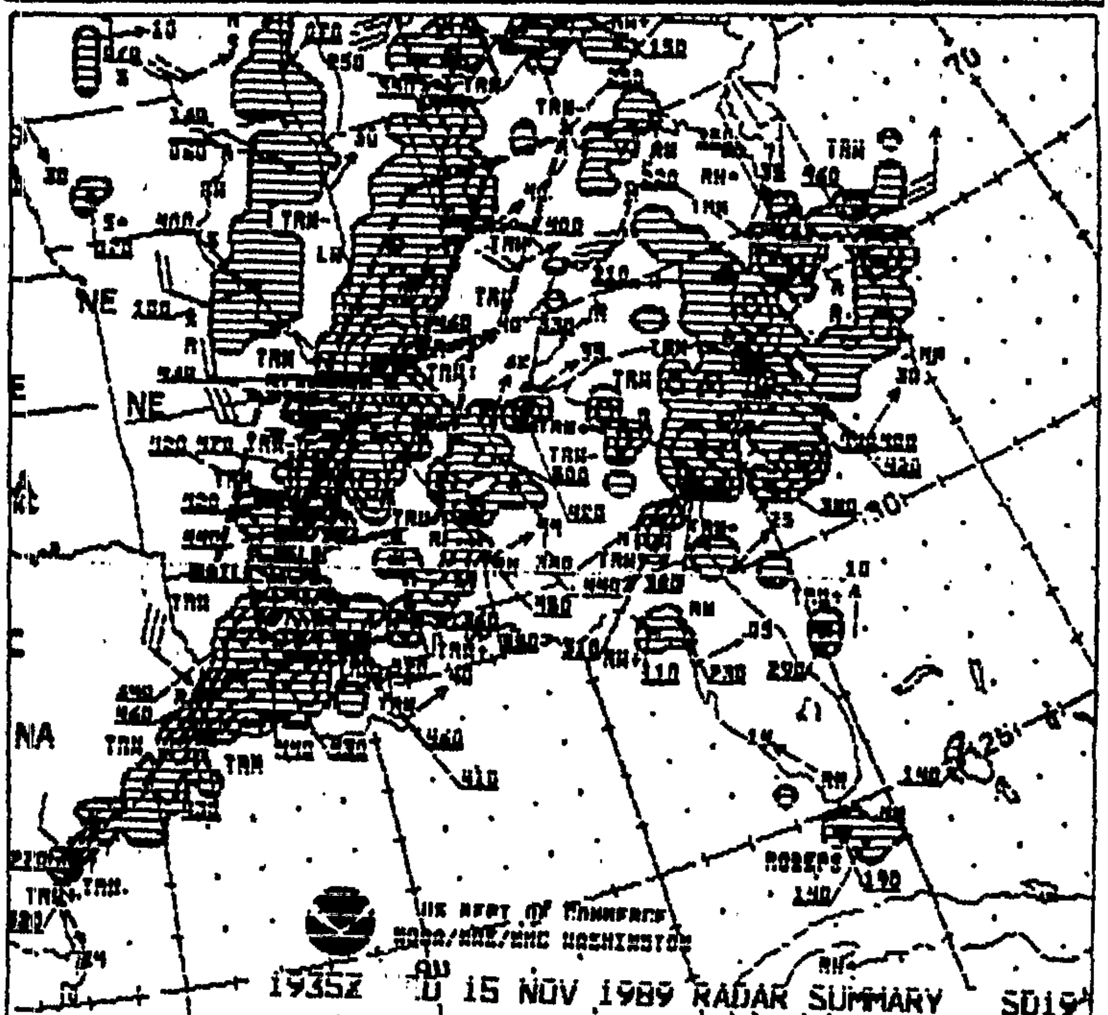
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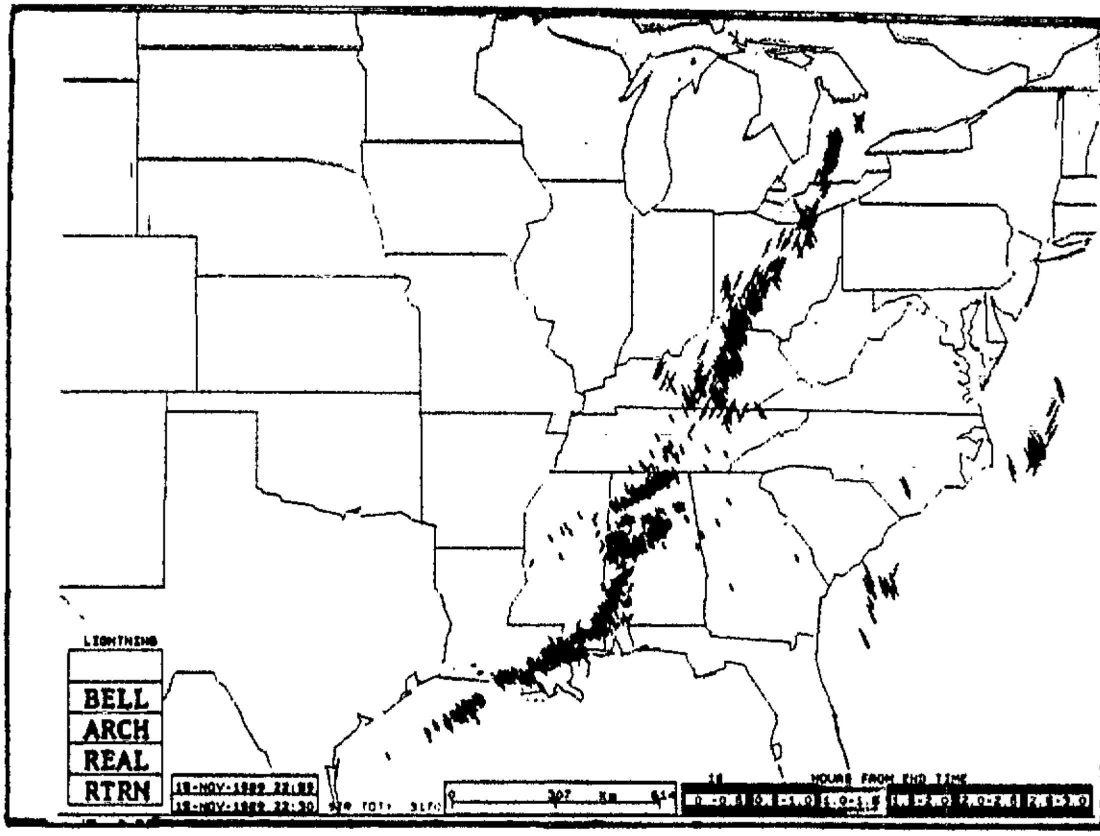
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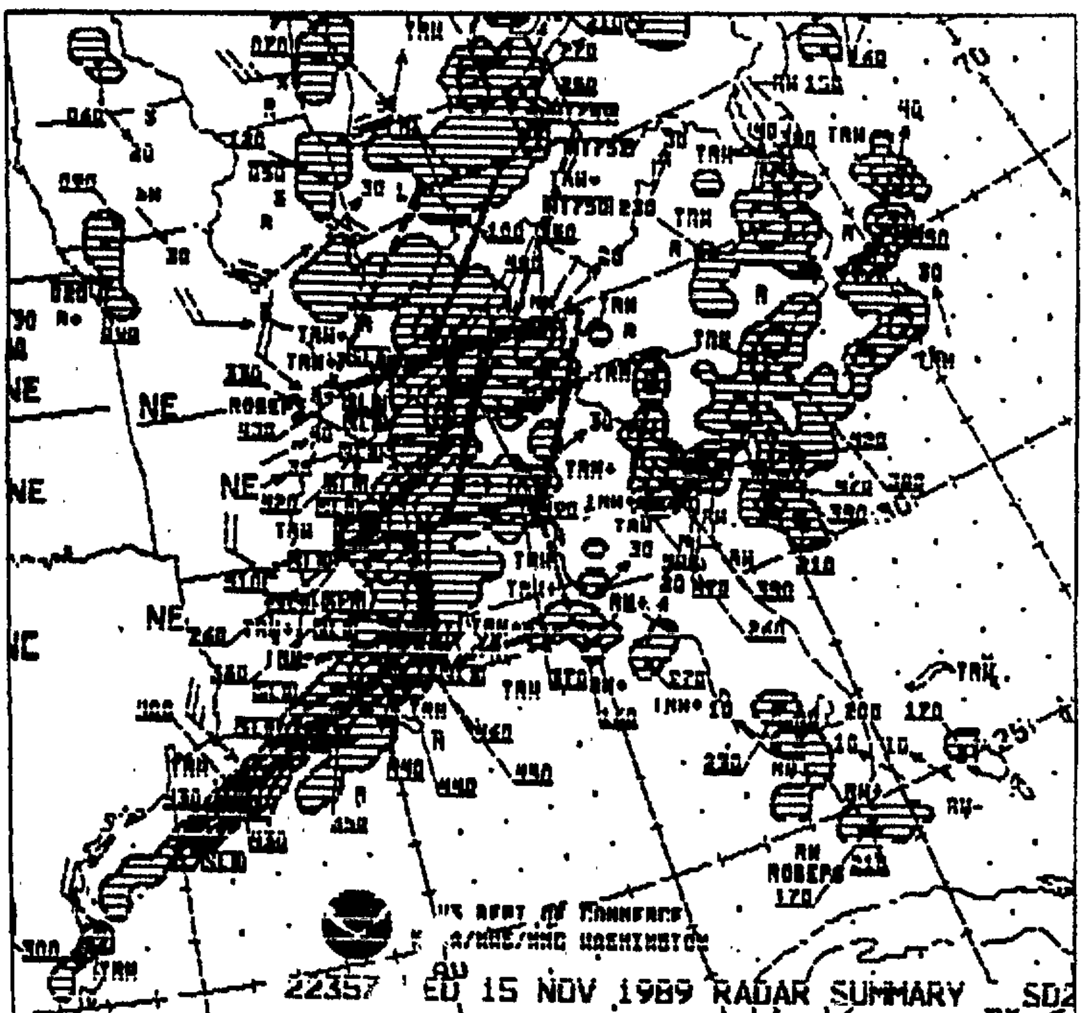
HOURS FROM END TIME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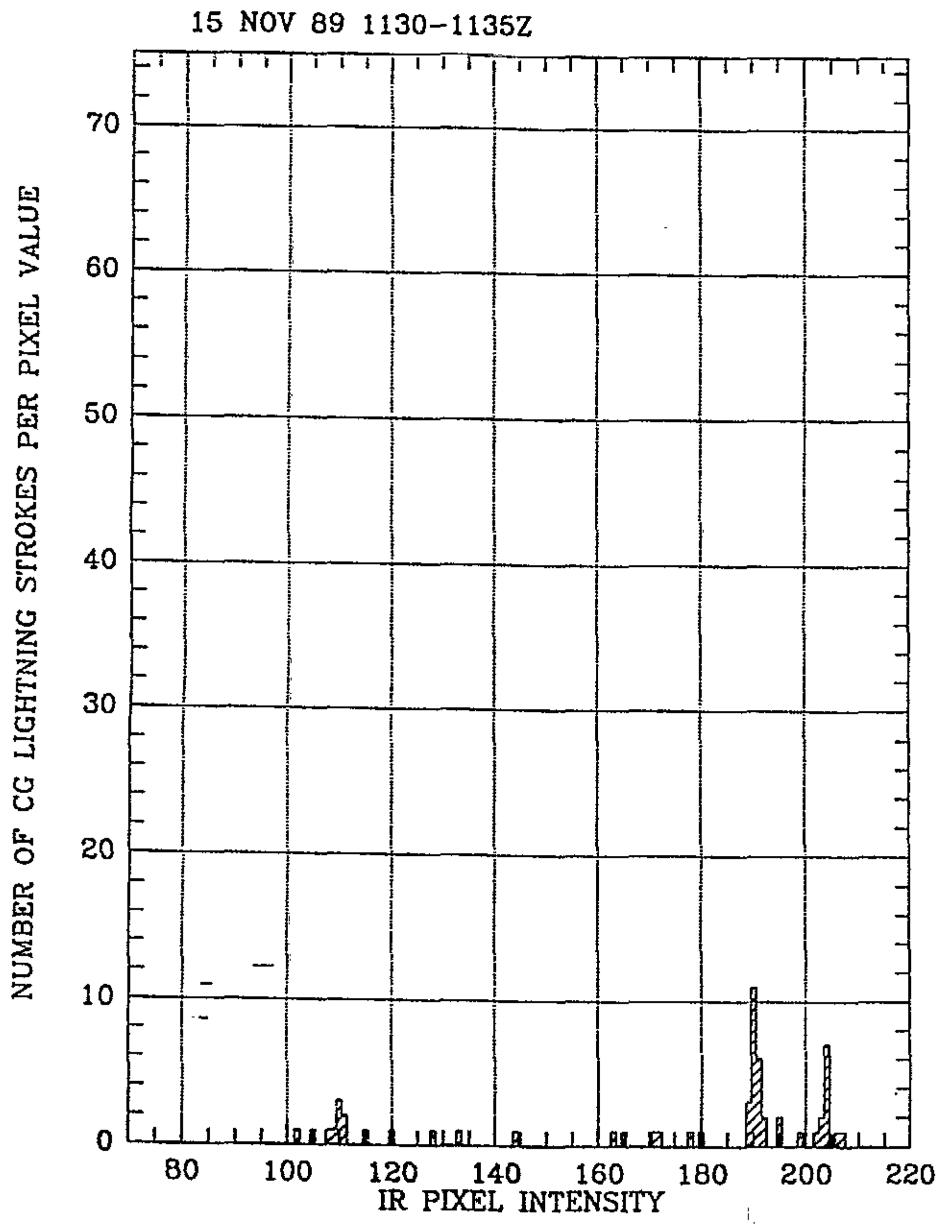
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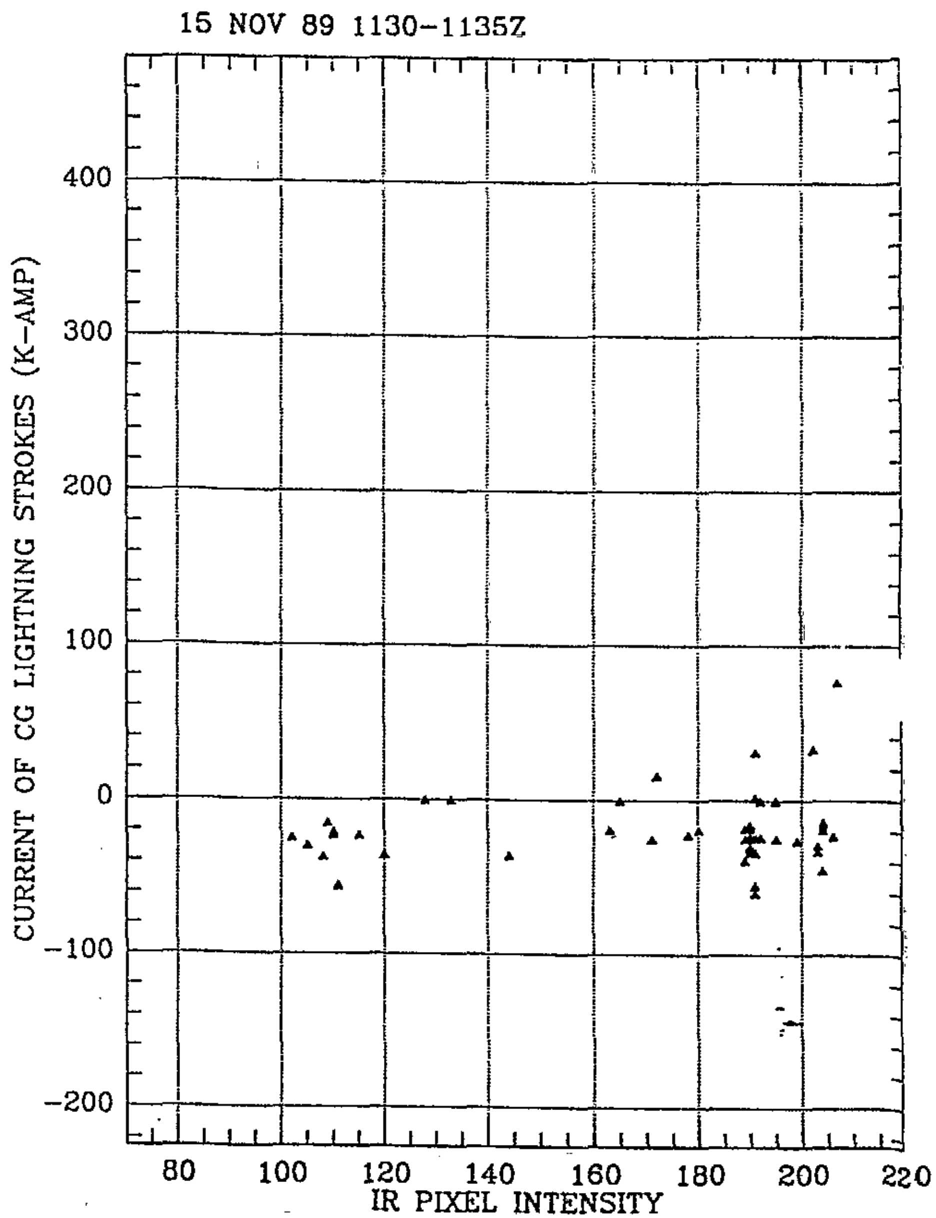
NUMBER OF CG LIGHTNING STROKES PER PIXEL VALUE
IR PIXEL INTENSITY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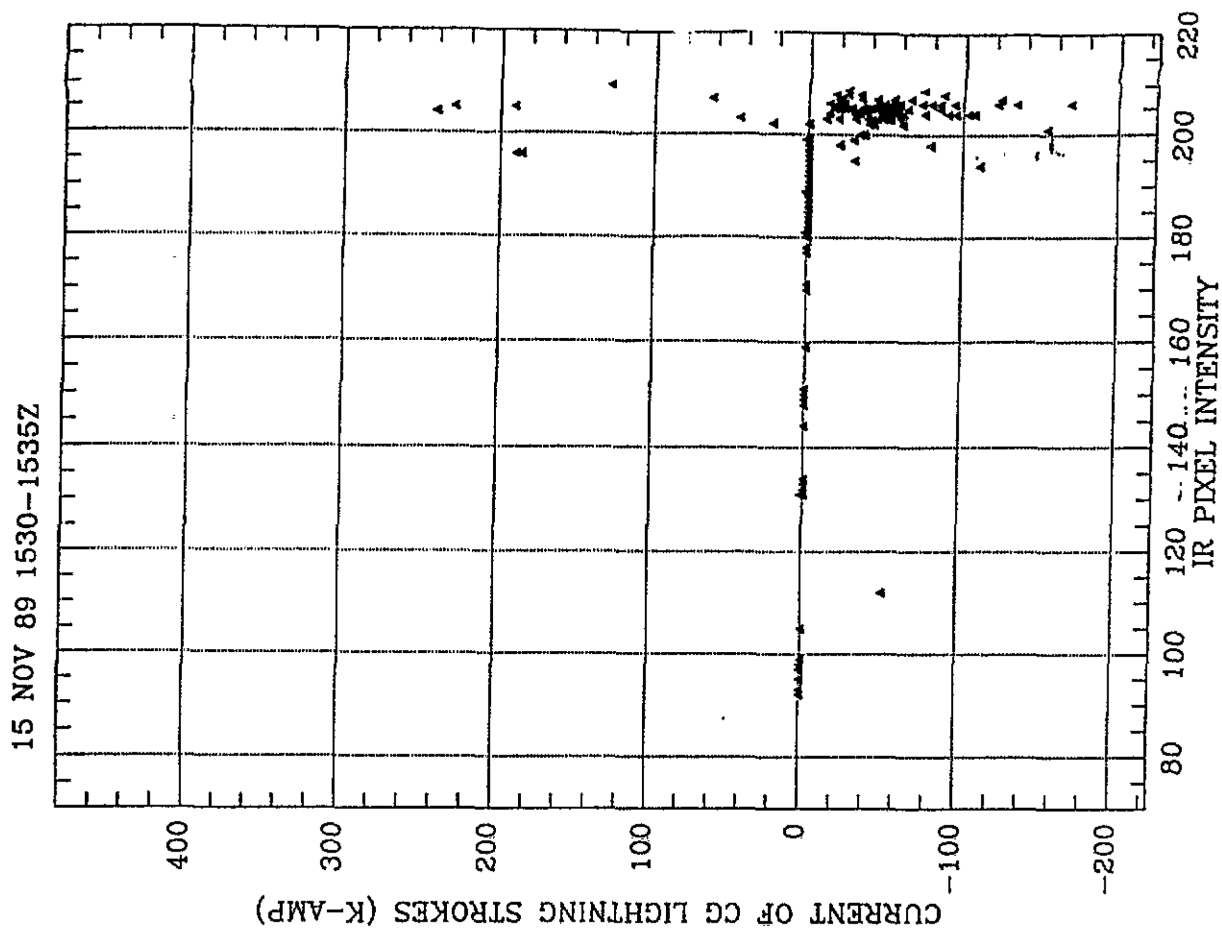
CURRENT OF CG LIGHTNING STROKES (K-AMP)
IR PIXEL INTENSITY



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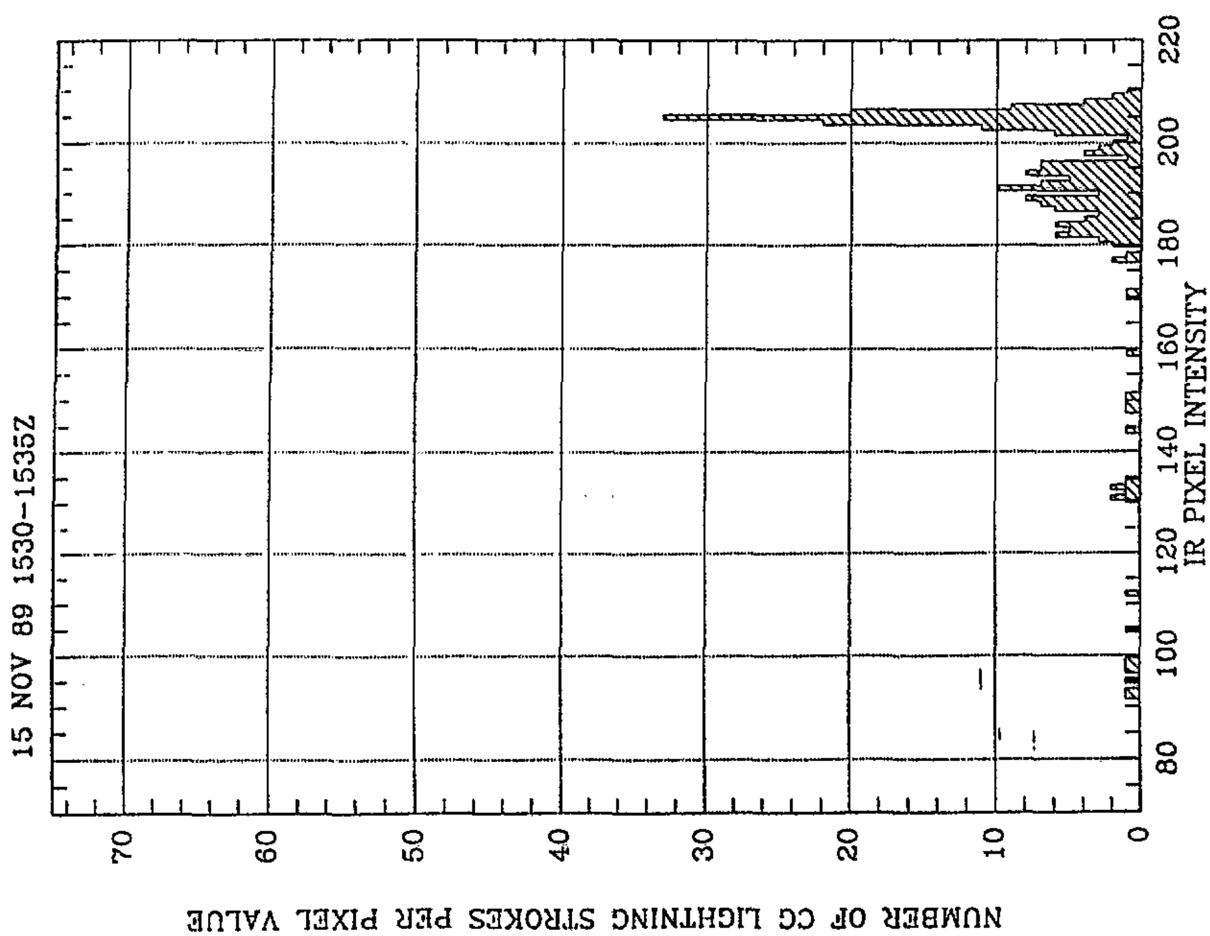
CURRENT OF CG LIGHTNING STROKES (K-AMP)
IR PIXEL INTENSITY



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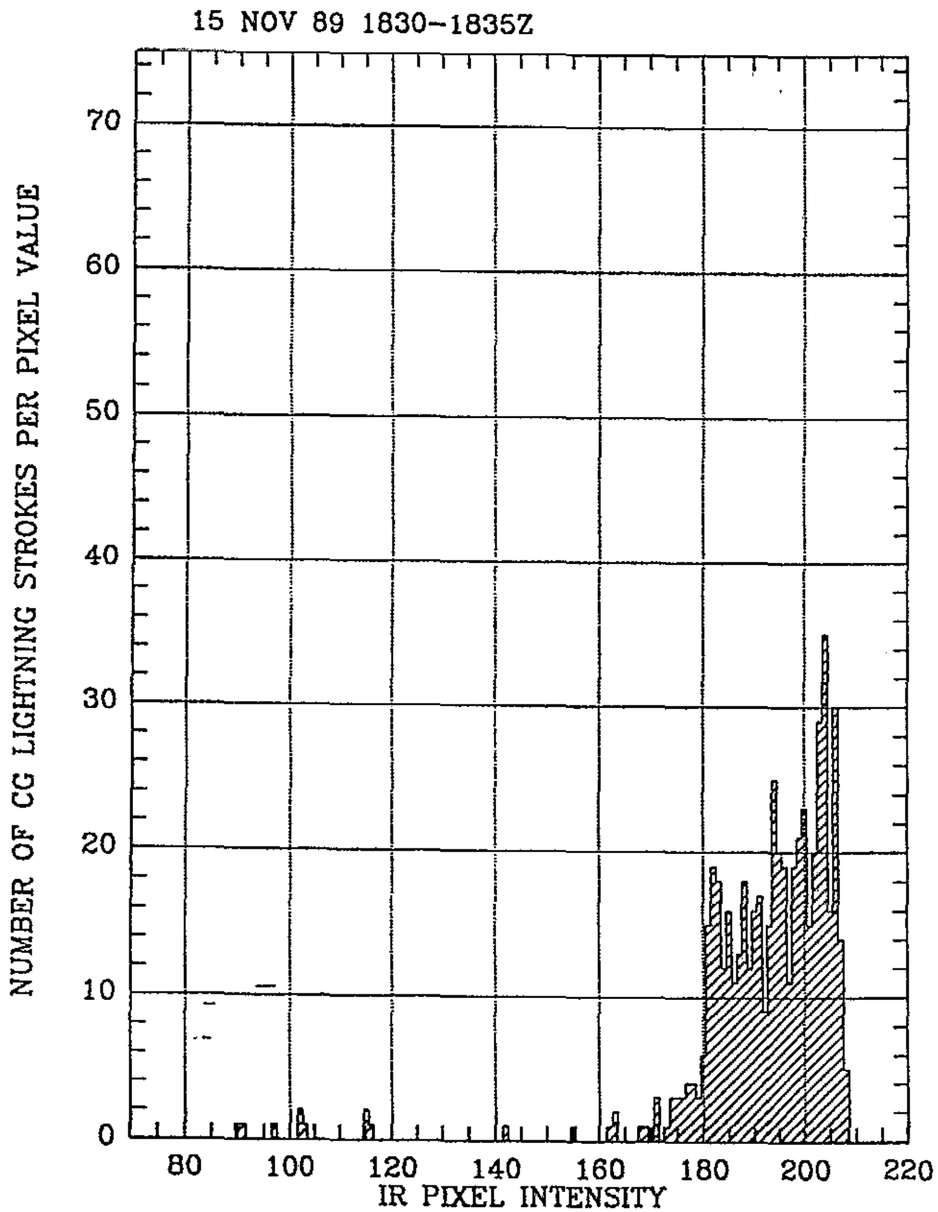
NUMBER OF CG LIGHTNING STROKES PER PIXEL VALUE
IR PIXEL INTENSITY



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NUMBER OF CG LIGHTNING STROKES PER PIXEL VALUE
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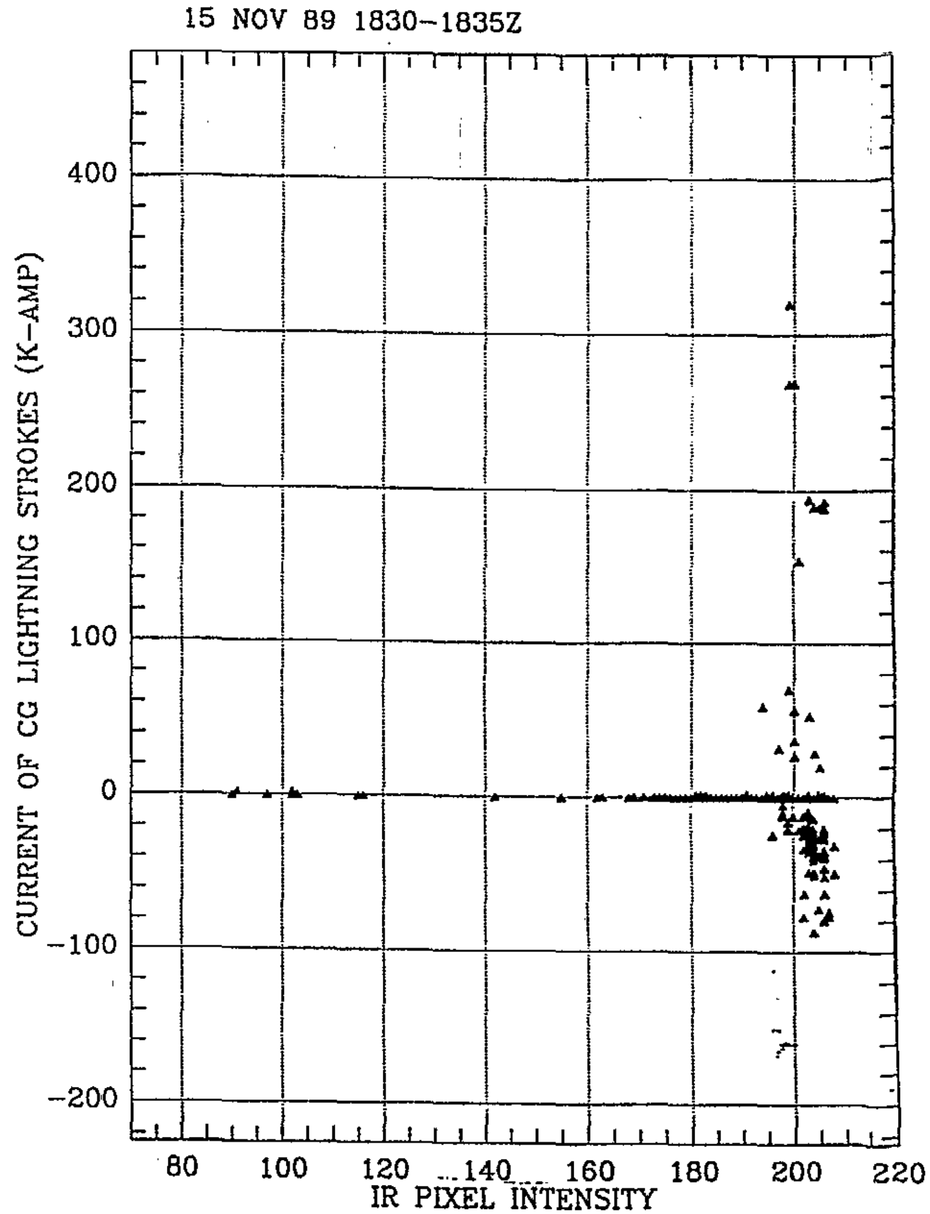
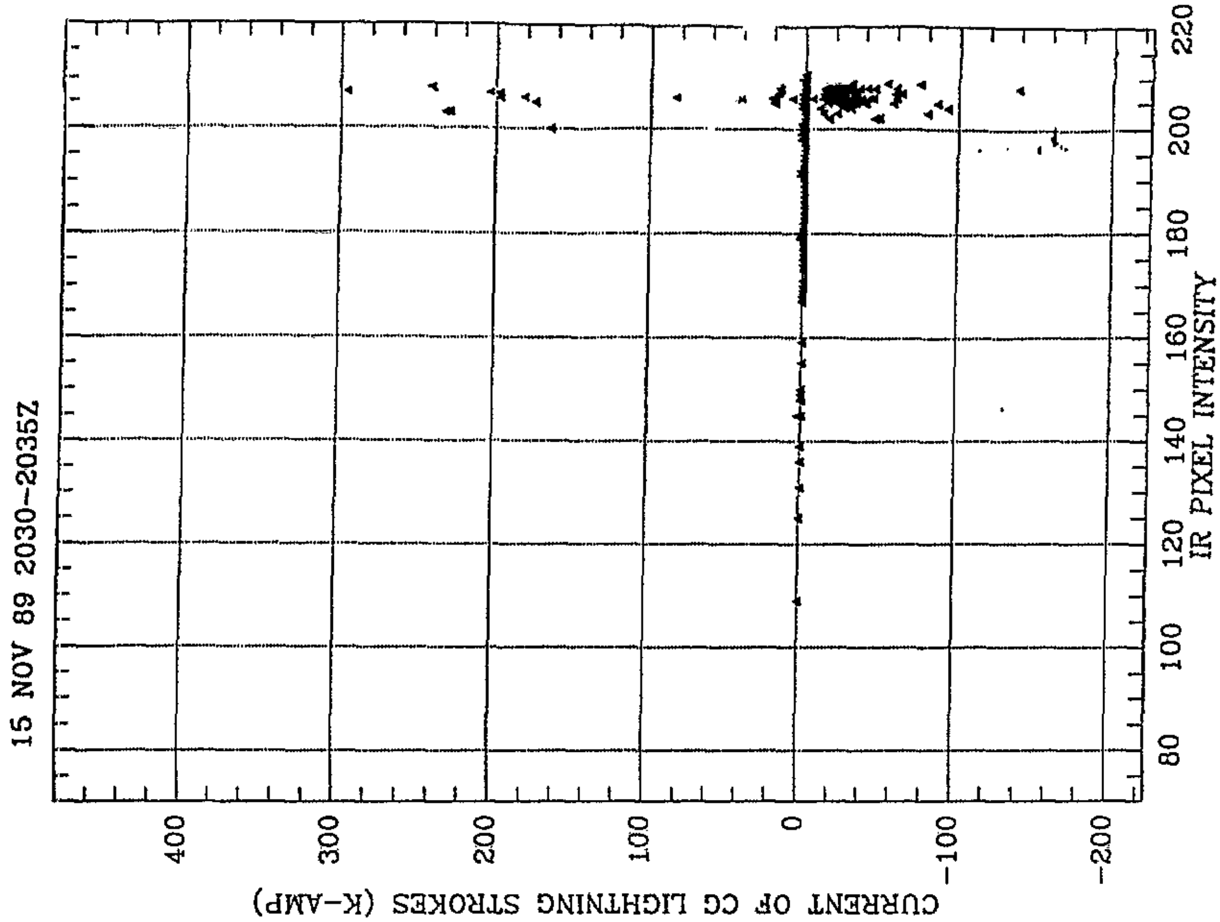
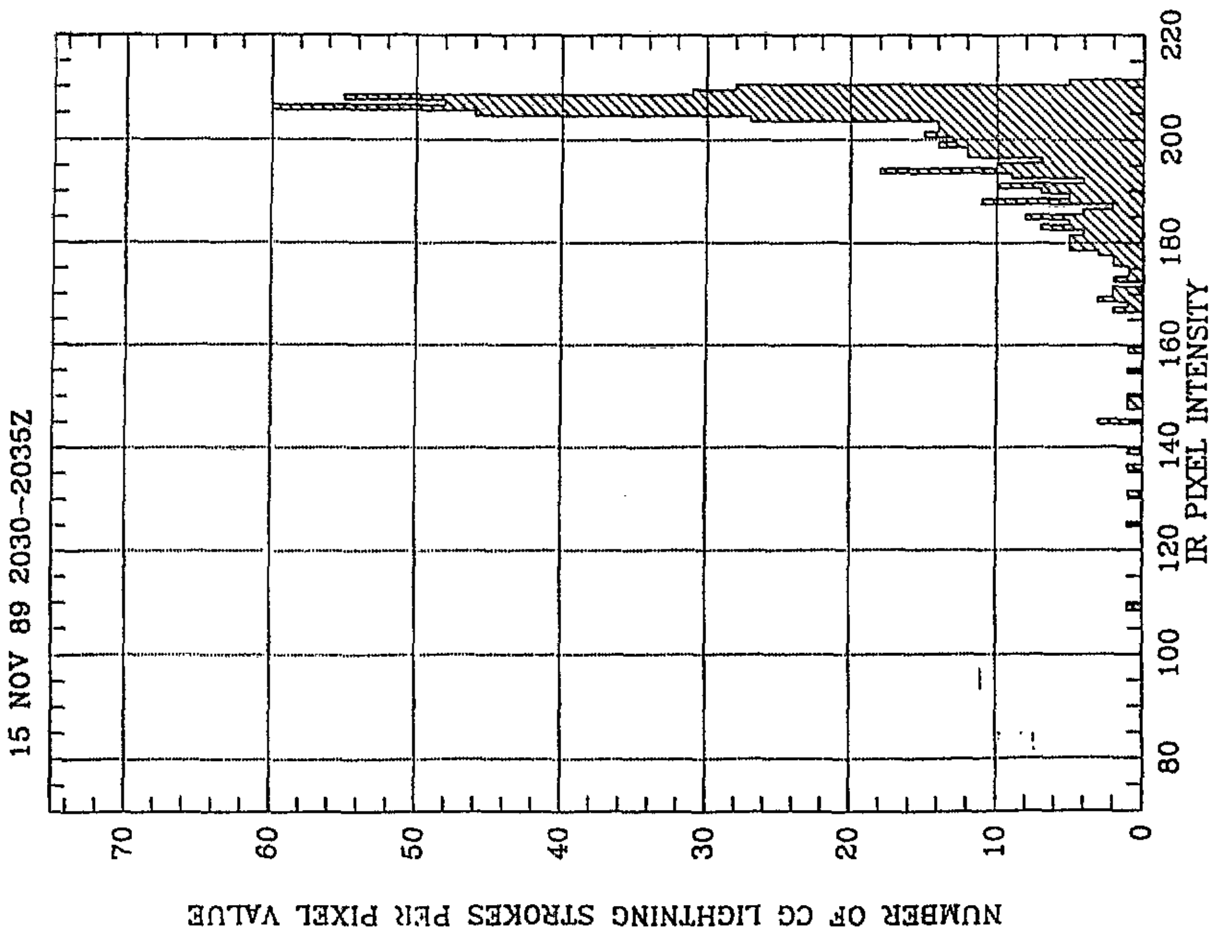
10
20
30
40
50
60
70
80
100
120
140
160
180
200
220
IR PIXEL INTENSITY



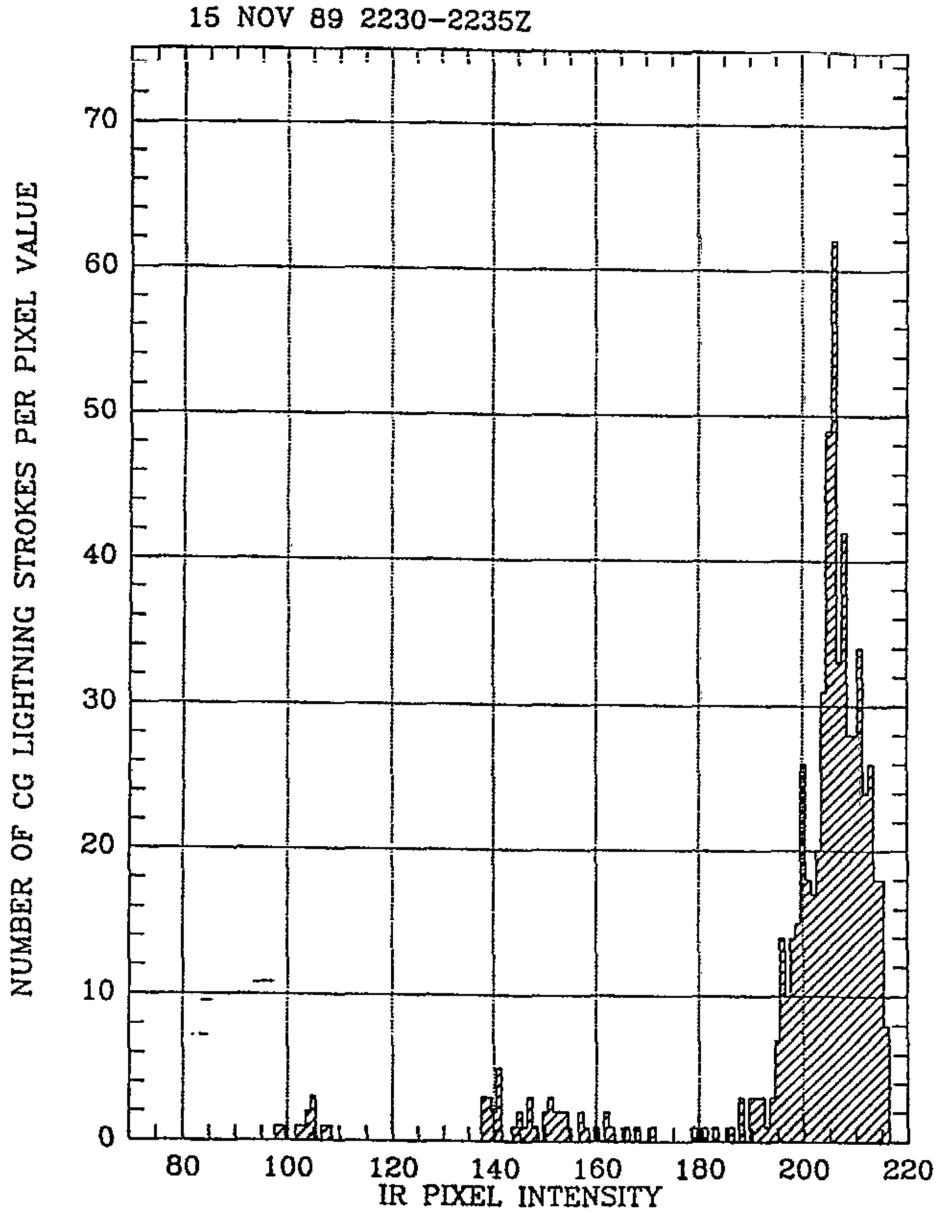
15 NOV 89 1830-1835Z
CURRENT OF CG LIGHTNING STROKES (K-AMP)
−200
−100
0
100
200
300
400
80
100
120
140
160
180
200
220
IR PIXEL INTENSITY



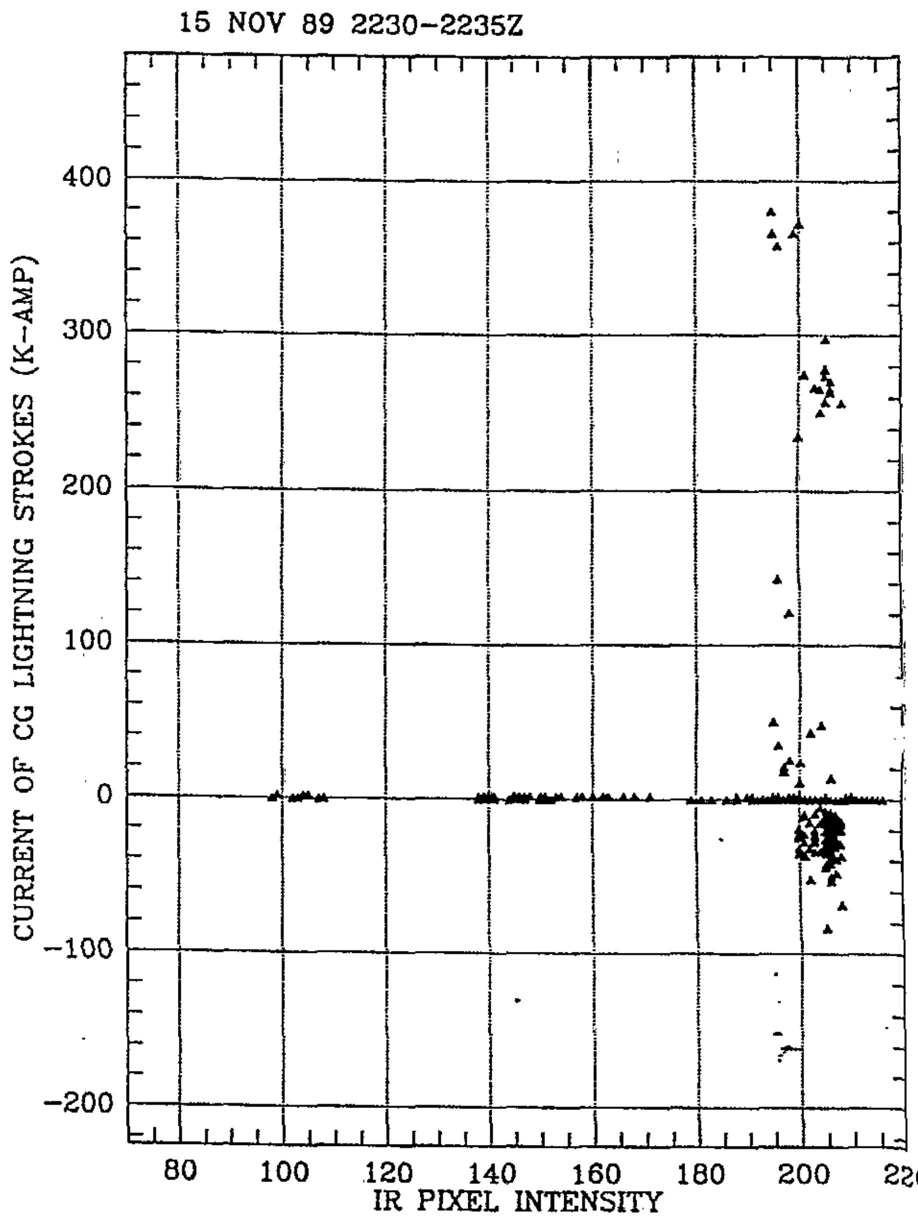
15 NOV 89 2030-2035Z
CURRENT OF CG LIGHTNING STROKES (K-AMP)
400
300
200
100
0
-100
-200
IR PIXEL INTENSITY
80
100
120
140
160
180
200
220



15 NOV 89 2030-2035Z
NUMBER OF CG LIGHTNING STROKES PER PIXEL VALUE
70
60
50
40
30
20
10
0
IR PIXEL INTENSITY
80
100
120
140
160
180
200
220



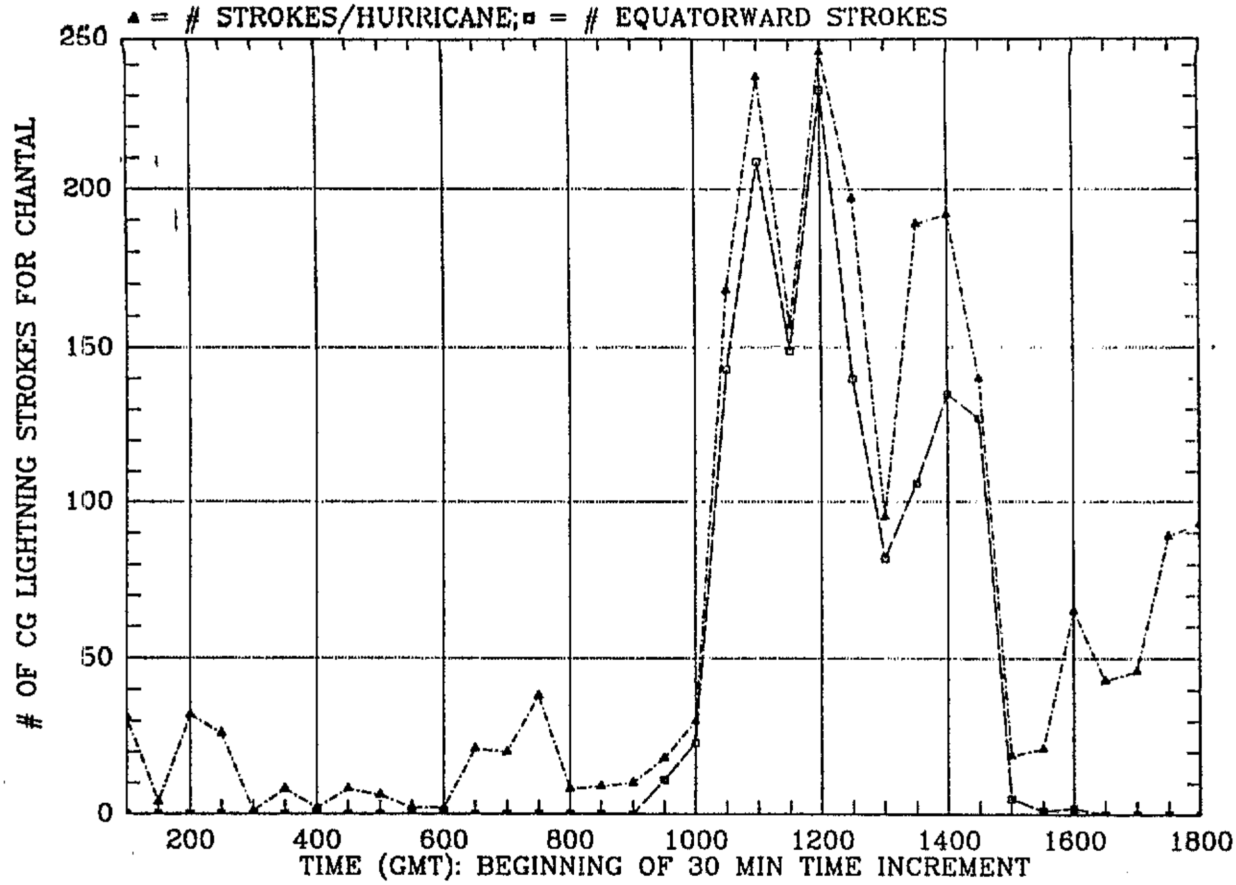
15 NOV 89 2230-2235Z
NUMBER OF CG LIGHTNING STROKES PER PIXEL VALUE
0
10
20
30
40
50
60
70
80
100
120
140
160
180
200
220
IR PIXEL INTENSITY

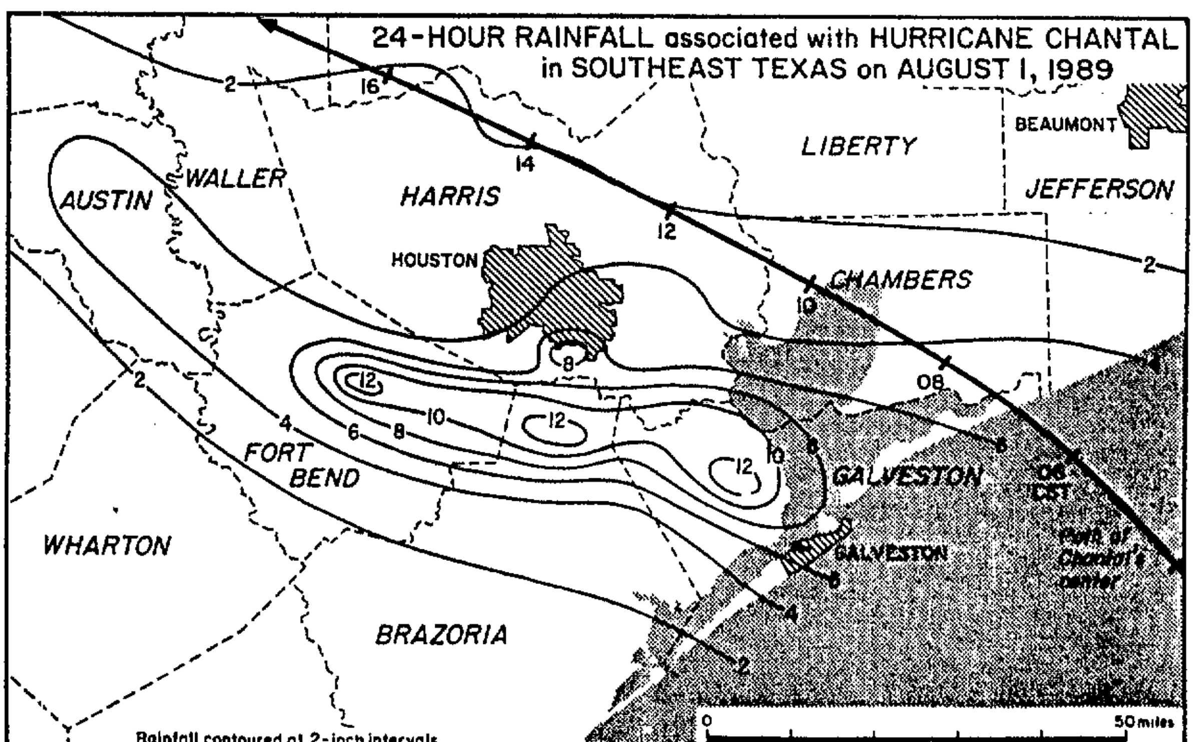


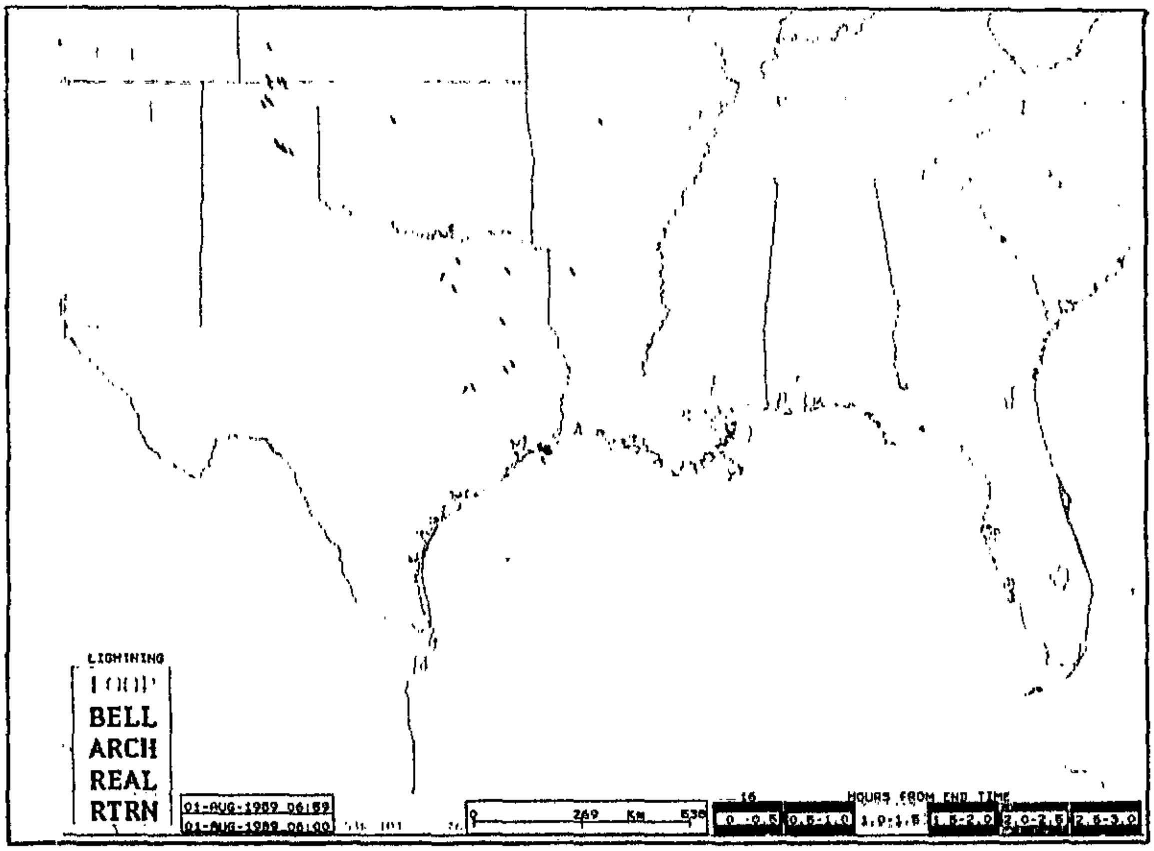
15 NOV 89 2230-2235Z
CURRENT OF CG LIGHTNING STROKES (K-AMP)
−200
−100
0
100
200
300
400
80
100
120
140
160
180
200
220
IR PIXEL INTENSITY

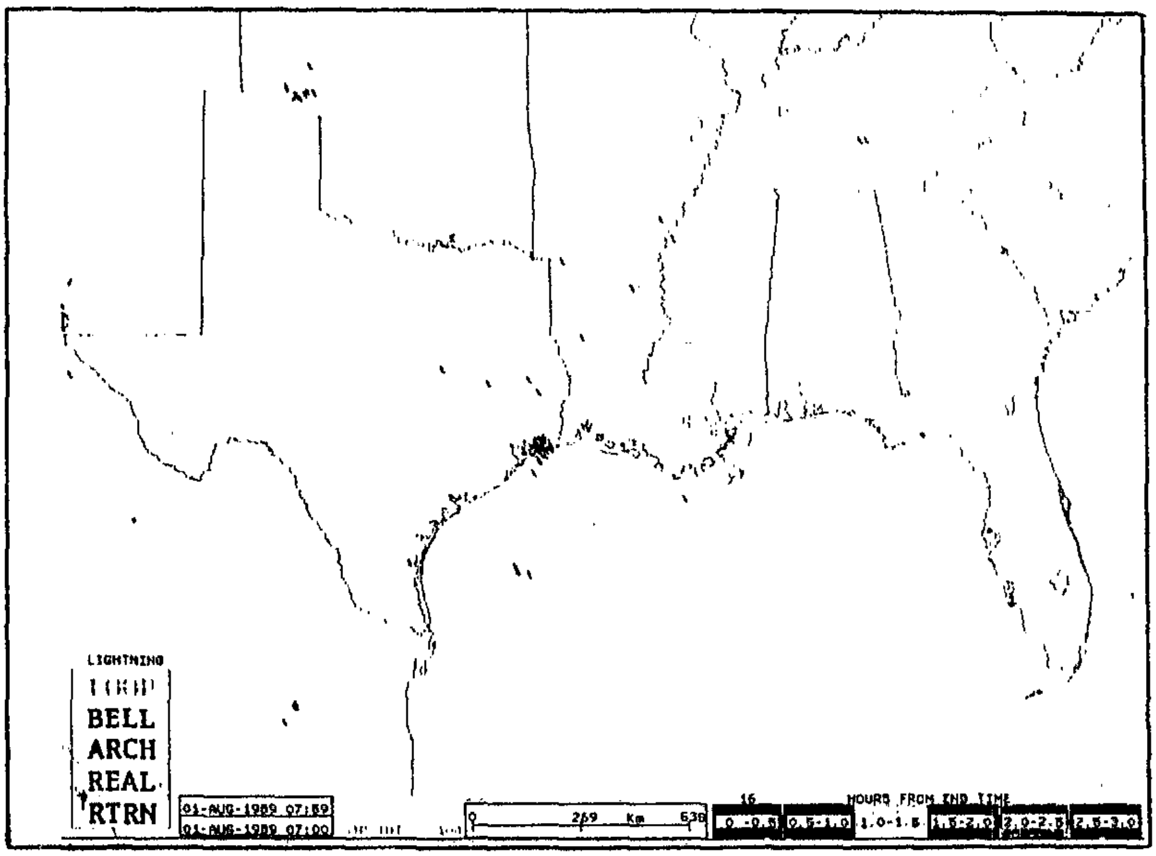
Case Study #2: Hurricane Chantal

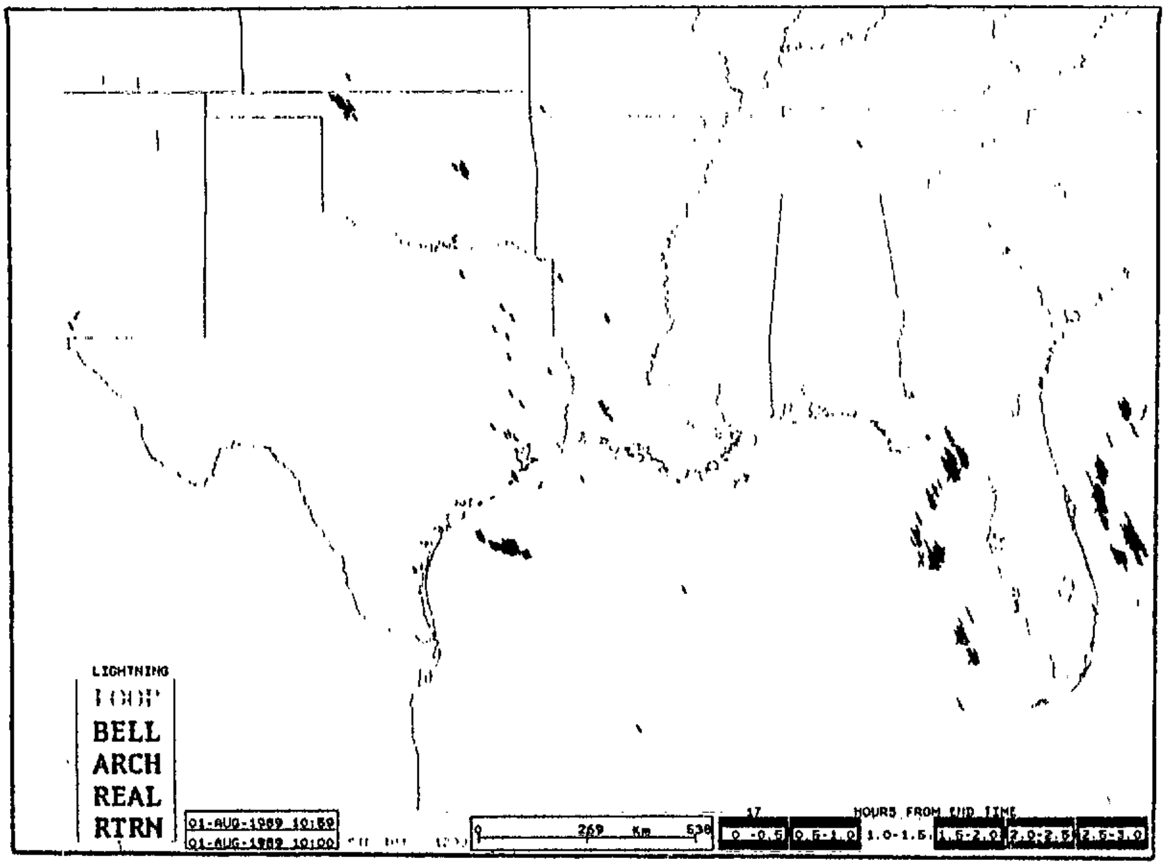
- Hurricane Evolution and Effect on U.S.
- Analysis of CG Lightning Activity
  - Landfall of Spiral Band Identified
  - Correlation to Heavy Precipitation
  - Equatorward "Bursts"
- Correlation of GOES Imagery to LPATS Data

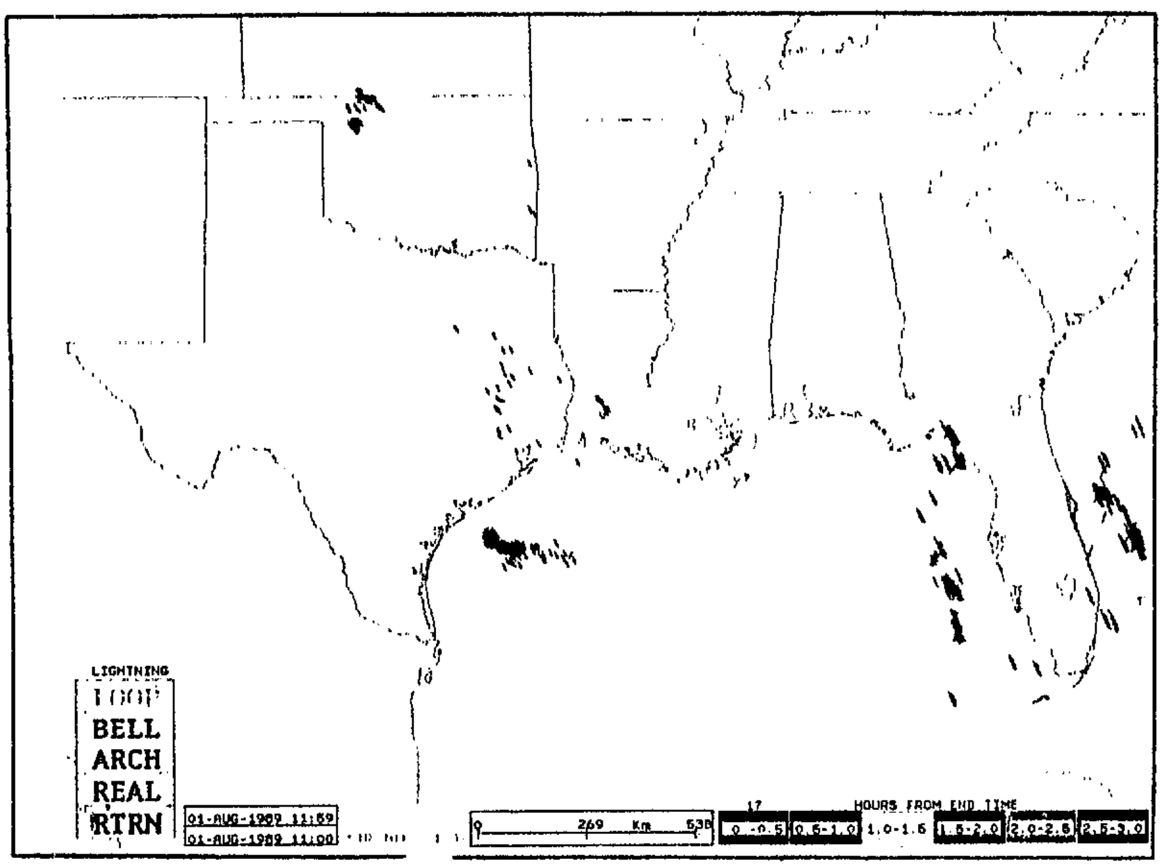

▲ = # STROKES/HURRICANE; ▫ = # EQUATORWARD STROKES
OF CG LIGHTNING STROKES FOR CHANTAL
TIME (GMT): BEGINNING OF 30 MIN TIME INCREMENT
0
50
100
150
200
250
200
400
600
800
1000
1200
1400
1600
1800

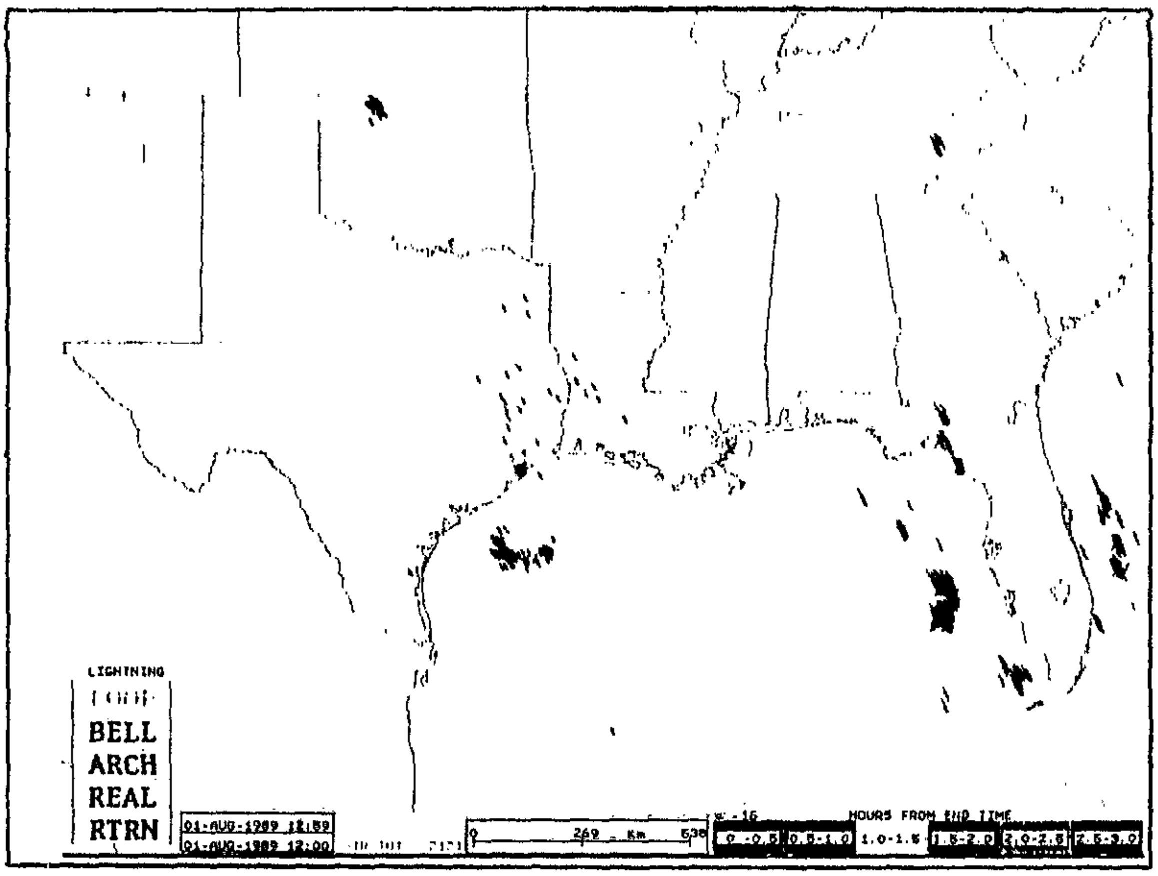

24-HOUR RAINFALL associated with HURRICANE CHANTAL in SOUTHEAST TEXAS on AUGUST 1, 1989
LIBERTY
BEAUMONT
JEFFERSON
AUSTIN
WALLER
HARRIS
HOUSTON
CHAMBERS
FORT BEND
GALVESTON
WHARTON
BRAZORIA
Path of Chantal's center
Rainfall contoured at 2-inch intervals.
0
50 miles

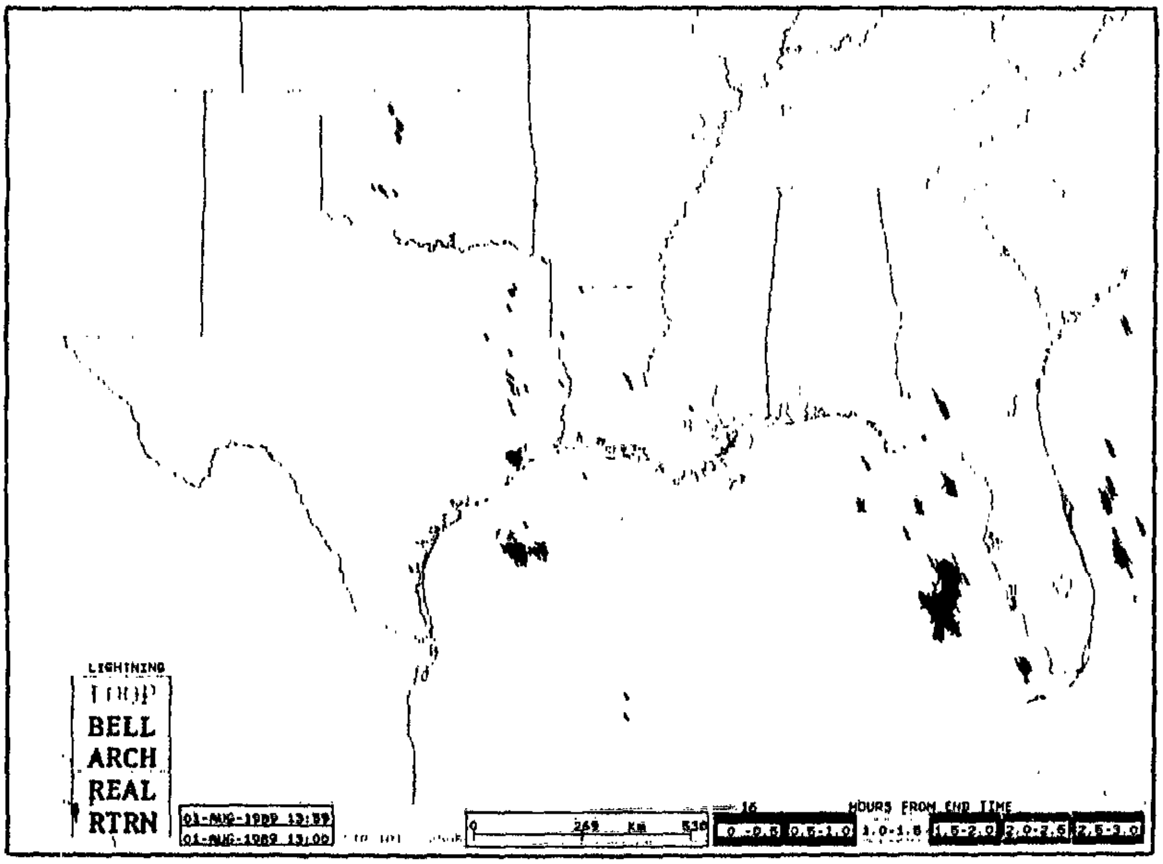

LIGHTNING
BELL
ARCH
REAL
RTRN
01-AUG-1989 06:59
01-AUG-1989 06:00
269 Km 538
16
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0

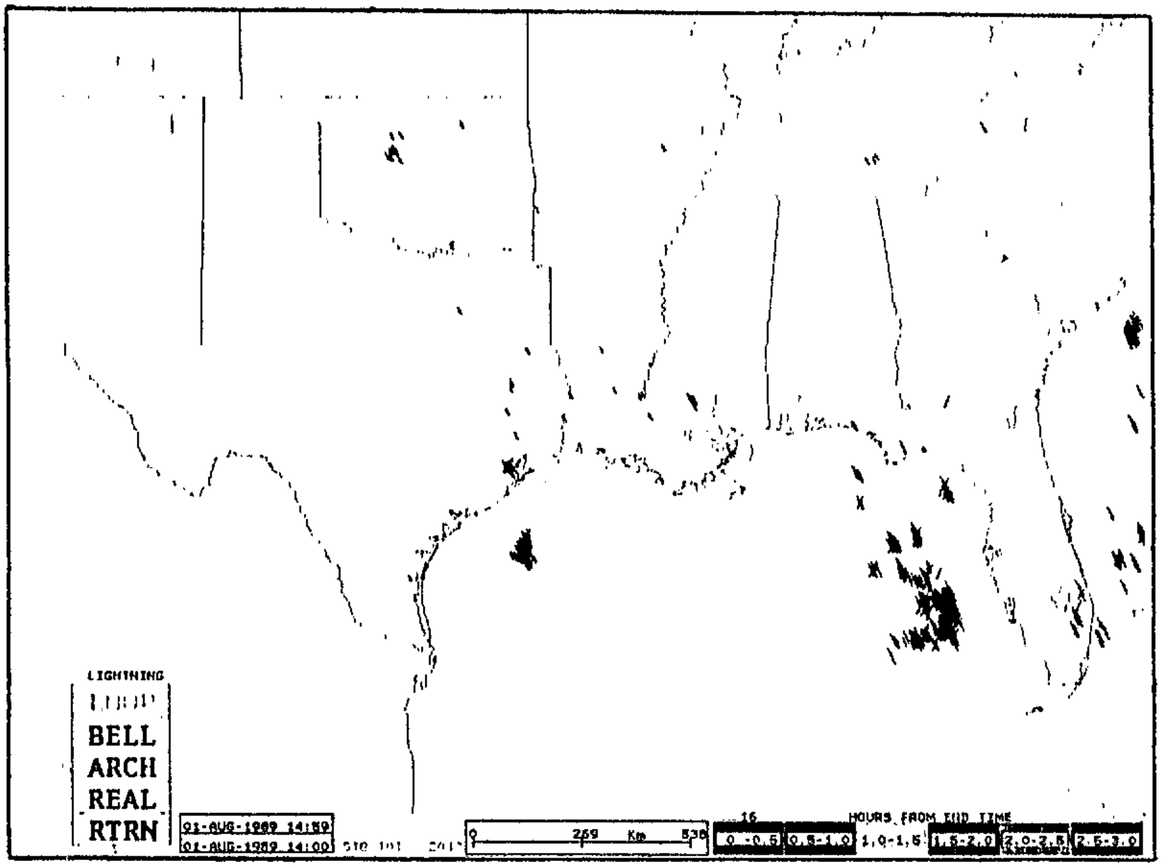

LIGHTNING
BELL
ARCH
REAL
RTRN
01-AUG-1989 07:59
01-AUG-1989 07:00
269 Km 538
16
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0

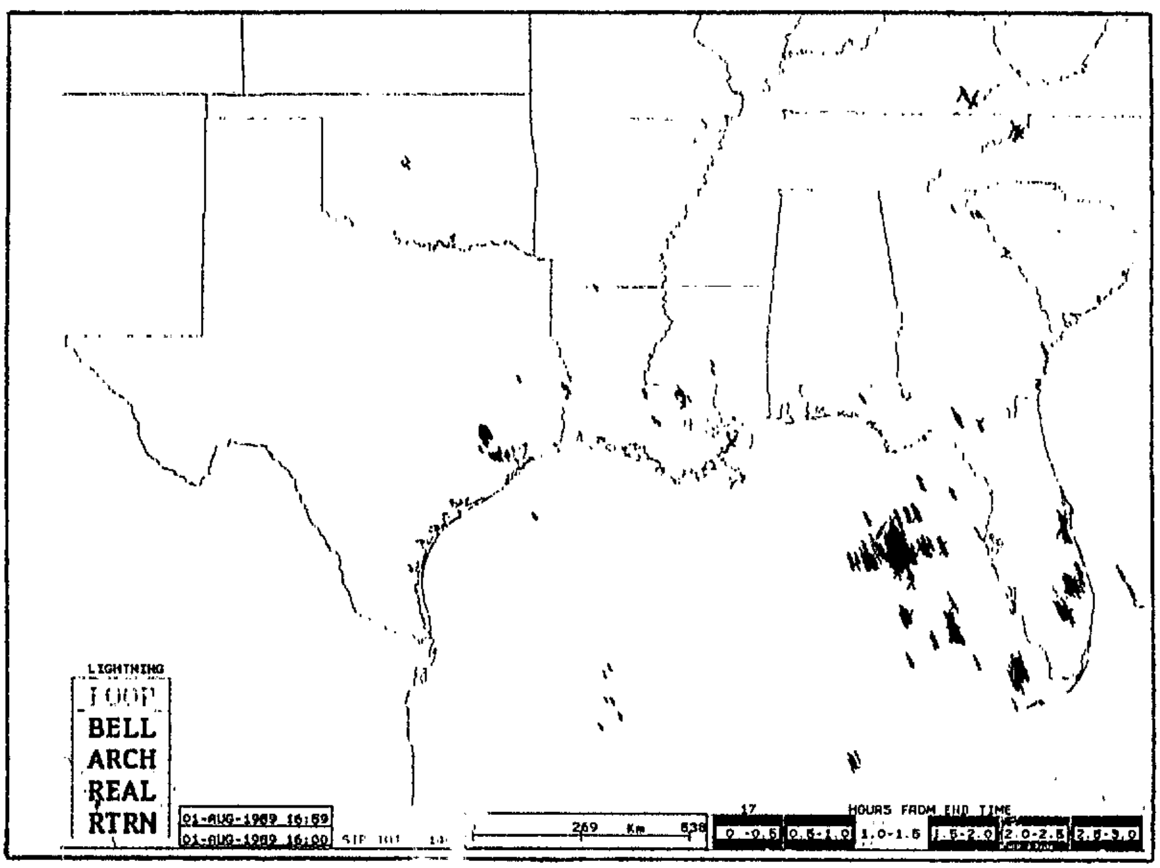

LIGHTNING
LOOP
BELL
ARCH
REAL
RTRN
01-AUG-1989 10:59
01-AUG-1989 10:00
0
269 Km
538
17
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0


LIGHTNING
LOOP
BELL
ARCH
REAL
RTRN
01-AUG-1989 11:59
01-AUG-1989 11:00
0
269 Km
538
17
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0


LIGHTNING
BELL
ARCH
REAL
RTRN
01-AUG-1989 12:59
01-AUG-1989 12:00
269 Km 538
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0


LIGHTNING
BELL
ARCH
REAL
RTRN
01-AUG-1989 13:59
01-AUG-1989 13:00
269 Km 538
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0


LIGHTNING
LOOP
BELL
ARCH
REAL
RTRN
01-AUG-1989 14:59
01-AUG-1989 14:00
0
269
Km
538
16
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0


LIGHTNING
LOOP
BELL
ARCH
REAL
RTRN
01-AUG-1989 16:59
01-AUG-1989 16:00
269
Km
538
17
HOURS FROM END TIME
0 -0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
2.5-3.0

Conclusion

- Major Findings
  - Linearity of Convection Defined by LPATS Data
  - Plots Matching CG Stroke Currents and GOES IR Pixel Intensities Can Aid in Forecasting Weather Systems
  - Lightning Activity Helps to Define Stages of Hurricane Activity

U.S. ARMY TECOM
WHITE SANDS
METEOROLOGICAL TEAM

DON THORNLEY
CHIEF
WHITE SANDS MET TEAM

LIGHTNING LOCATION PROTECTION SYSTEM (LLP)

BRIEFING OUTLINE

* SYSTEM OVERVIEW
* HOW IT IS USED

LIGHTNING LOCATION PROTECTION SYSTEM (LLP)

SYSTEM OVERVIEW

* SENSORS
* DISPLAY

LIGHTNING LOCATION PROTECTION SYSTEM (LLP)

HOW IT IS USED

LIGHTNING FCST TOOLS

TOOL	SCALE
CHARTS	GLOBAL
MIDDS	NATIONAL
LLP	STATE
RADAR	REGION
SAMS	RANGE

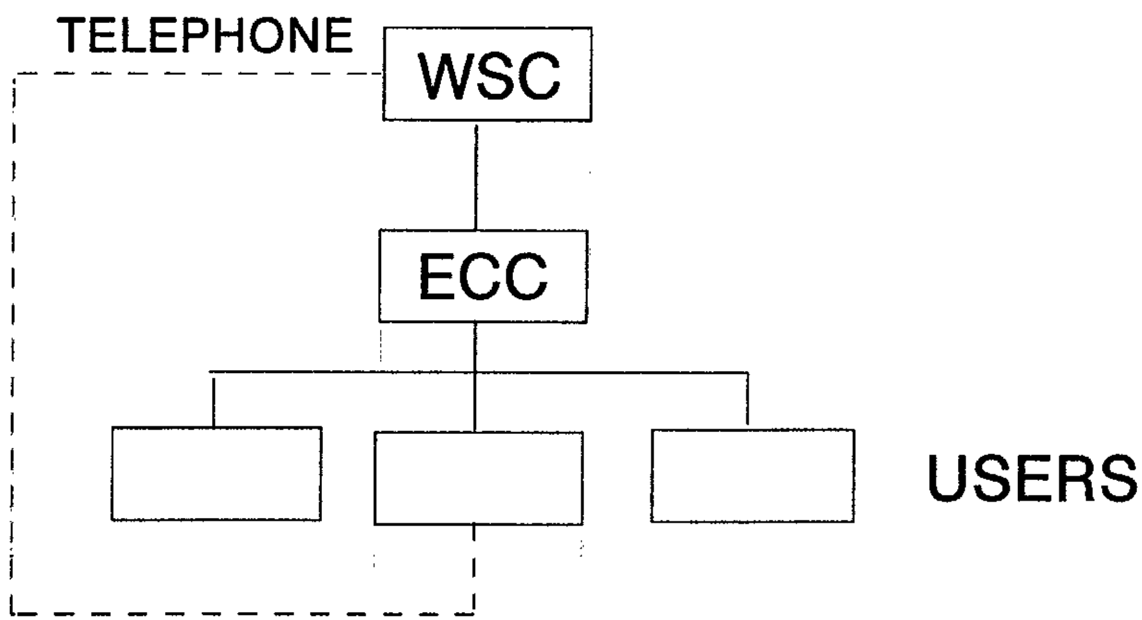
LIGHTNING LOCATION PROTECTION SYSTEM (LLP)

ADVANTAGES

* MEASURES LIGHTNING DIRECTLY
* CONVENIENT SCALE
* LOW MAINTENANCE

LIGHTNING LOCATION PROTECTION SYSTEM (LLP)

NOTIFICATION



Lightning Detection Data Use in National Weather Service Forecast Office Operations

Presented by
Brenda Graham[1]

Thunderstorms can definitely be objects of both beauty and destruction. It is well documented that thunderstorms cause property damage and endanger lives. Lightning is the second leading cause of all weather related fatalities in the United States. Only flooding results in more deaths than lightning (NOAA/PA 92053).

Because the National Weather Service's (NWS) primary mandate is the protection of life and property, NWS forecasters have a significant interest in thunderstorms. Remote sensing of thunderstorms can be invaluable to NWS operations when trying to anticipate Mother Nature's fickle ways. Forecasters relied on satellite imagery, radar, and human observations for thunderstorm detection before the advent of lightning detection networks. In the data-sparse West in particular, this meant some areas had poor detection efficiency.

There are two lightning detection networks used by the NWS. One is managed by Atmospheric Research Systems, Inc, (ARSI) of Palm Bay, Florida, and covers the entire nation. This system uses the Lightning Position and Tracking System (LPATS) time-of-arrival technology. The other network covers the 11 western states (of the continental U.S.) and is managed by the Bureau of Land Management (BLM) in Boise, Idaho. This network utilizes the Lightning Location and Protection, Inc., (LLP) direction finding technology and reports only cloud-to-ground strike data. The ARSI system will principally report cloud-to-ground lightning flashes, but some other types of lightning flashes (e.g. in-cloud, cloud-to-cloud) are also reported. In both cases, only the cloud-to-ground flash data is displayed to NWS forecasters in the form of near real-time computer graphics.

There is an important difference between the BLM and ARSI systems. The BLM system will report lightning flashes, whereas the ARSI system will report all the return strokes that occur during the flash (note that a lightning **flash** is composed of multiple **return strokes**).

NWS forecasters use cloud-to-ground lightning data primarily to evaluate storm tracks, verify or clarify radar data and satellite imagery, and detect the on-set of cloud-to-ground lightning flashes. The data may also serve as input for NWS watches and warnings for events like flash floods and severe thunderstorms.

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Below are descriptions of the following figures:

Figure 1....The system data flow from detector to NWS forecasters of the national (ARSI) and western (BLM) networks.

Figure 2....Examples of the national network contoured graphic received by NWS forecasters via the NWS's AFOS computer system. Note the bottom portion of the page is an enlarged, detailed view of the data. The "X" marks are return stroke "centers". The numbers are the total number of return strokes concentrated in that general area for the period 15 minutes prior to 1945Z, August 7 1992.

Figure 3....Examples of the BLM network contoured graphic received by NWS forecasters via the NWS's AFOS computer. Note the bottom portion of the page is an enlarged, detailed view of the data. The "X" marks are flash "centers". The numbers are the total number of lightning flashes concentrated in that general area for the period 30 minutes prior to 1945Z, August 7, 1992.

Figure 4....A side-by-side comparison of close-ups from Figures 2 and 3. The apparent differences are primarily due to ways the graphics are contoured and the LPATS tally of return strokes instead of lightning flashes.

While these graphics may not seem especially useful, they do have strong points: they are in summary form; they cover a large area; and the graphic representation allows for quick analysis. However, there are some drawbacks, too: the data is never presented in real-time; occasional bogus location reports are plotted; and the contouring tends to "bloom" the data, showing an affected area to be larger than it really is.

Overall, lightning detection data has become very valuable to NWS operations and would definitely be missed if unavailable.

REFERENCES:

Kessler, E., and White, G.F., 1981: "Thunderstorms in a Social Context", Thunderstorms: A Social, Scientific, and Technological Documentary, Vol. 1 - The Thunderstorm in Human Affairs, September 1981, pp 1-22, publication number GPO: 577-124-1982. Available from the U.S. Government Printing Office, Washington, DC, 20402.

Mielke, K.B., 1992: "LLP and LPATS - Two Different Lightning Mapping Technologies", NWS Western Region Technical Attachment Number 92-22, June 9, 1992. Available from NWS Western Region Scientific Services Division, Salt Lake City, UT, 4 pp.

National Weather Service [agency publication], 1992: "Thunderstorms and Lightning...The Underrated Killer!", National Oceanic and Atmospheric Administration Pamphlet #92053 (NOAA/PA 92053), Fall 1992. Available from the U.S. Government Printing Office, Washington, DC, 20402, 12 pp.

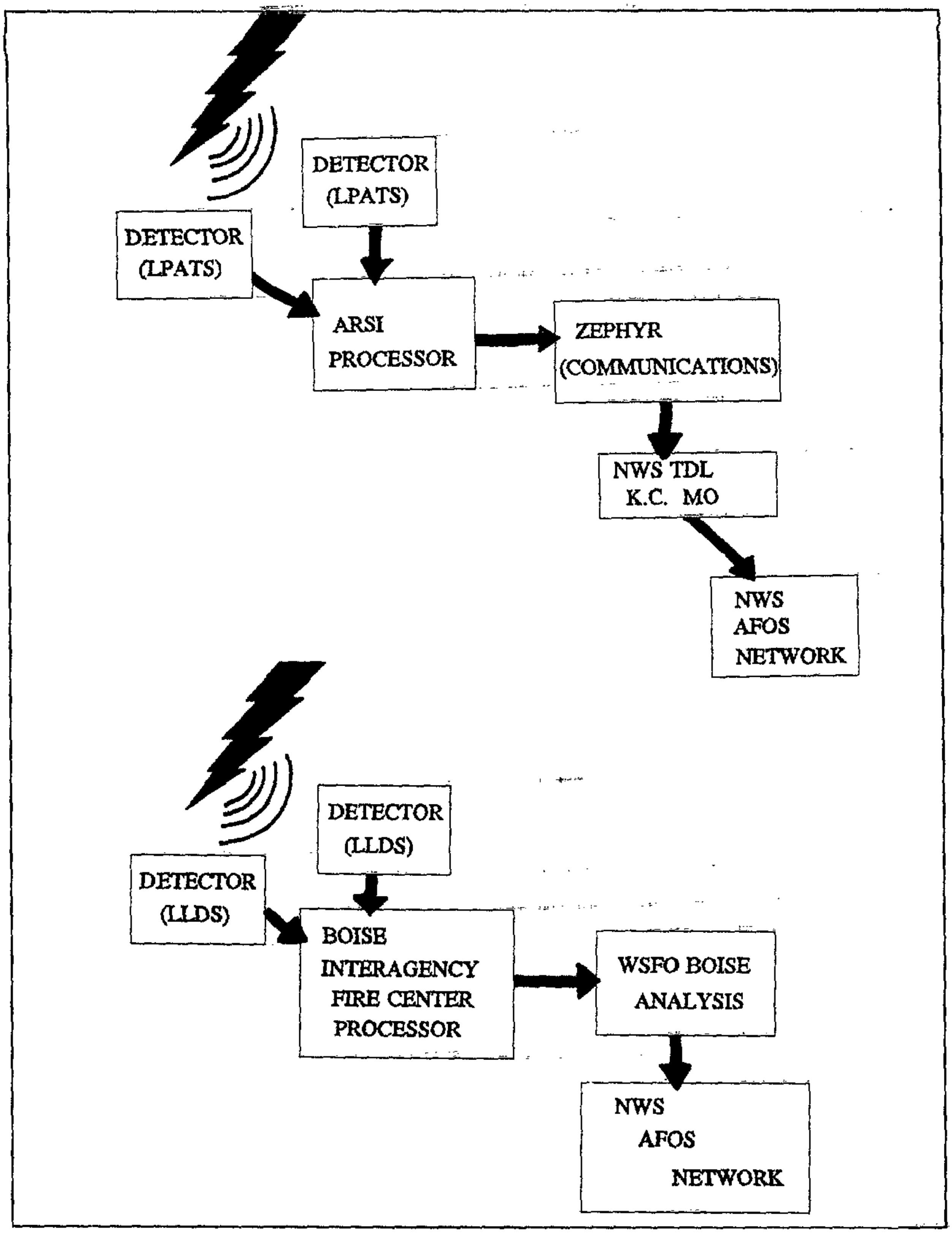


Figure 1. Data flow of the networks. Top: ARSI (LPATS). Bottom: BLM (LLP)

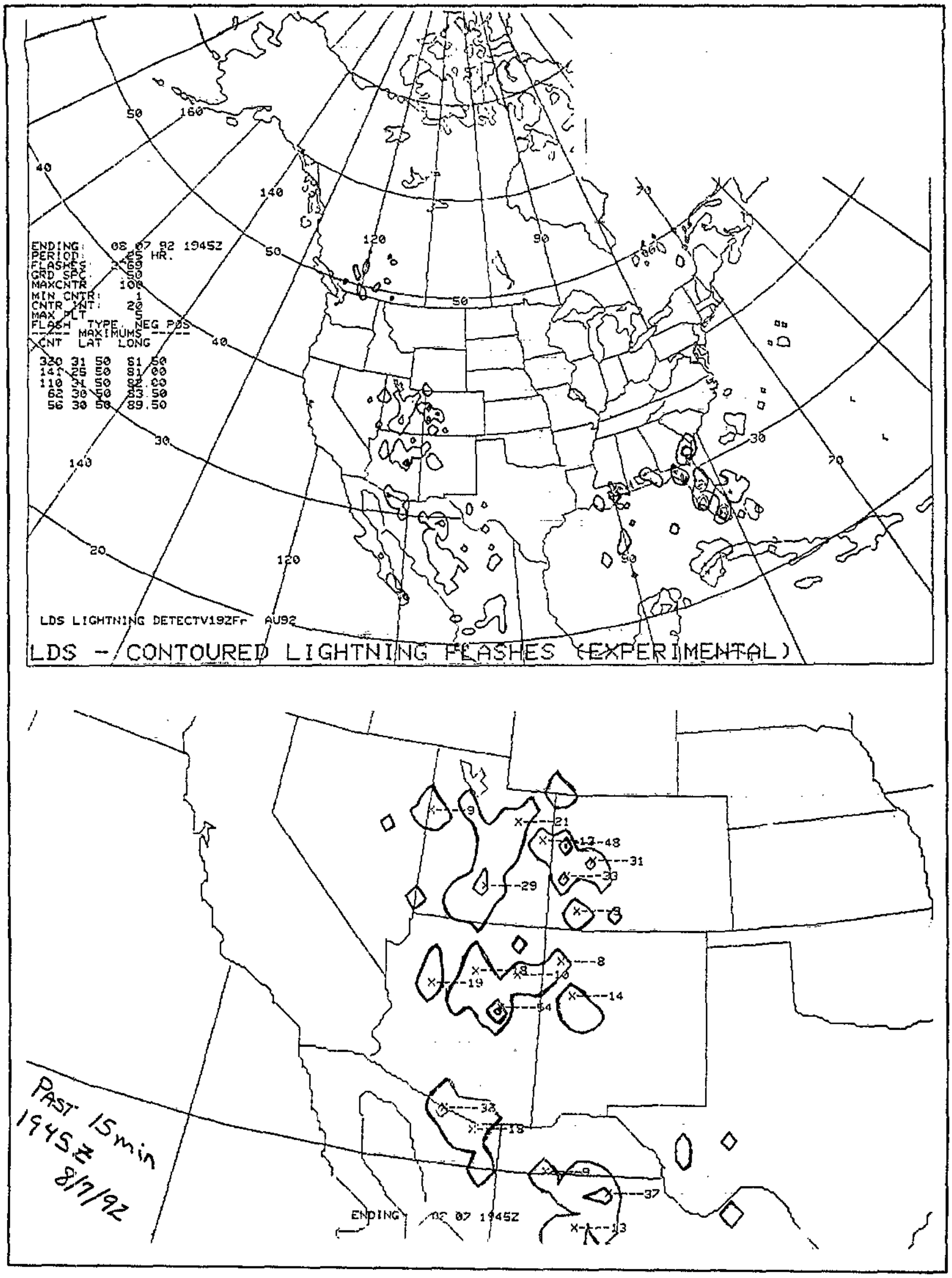


Figure 2. Examples of NWS graphic display of data (ARSI Network). Top: Entire network area. Bottom: Zoomed display.

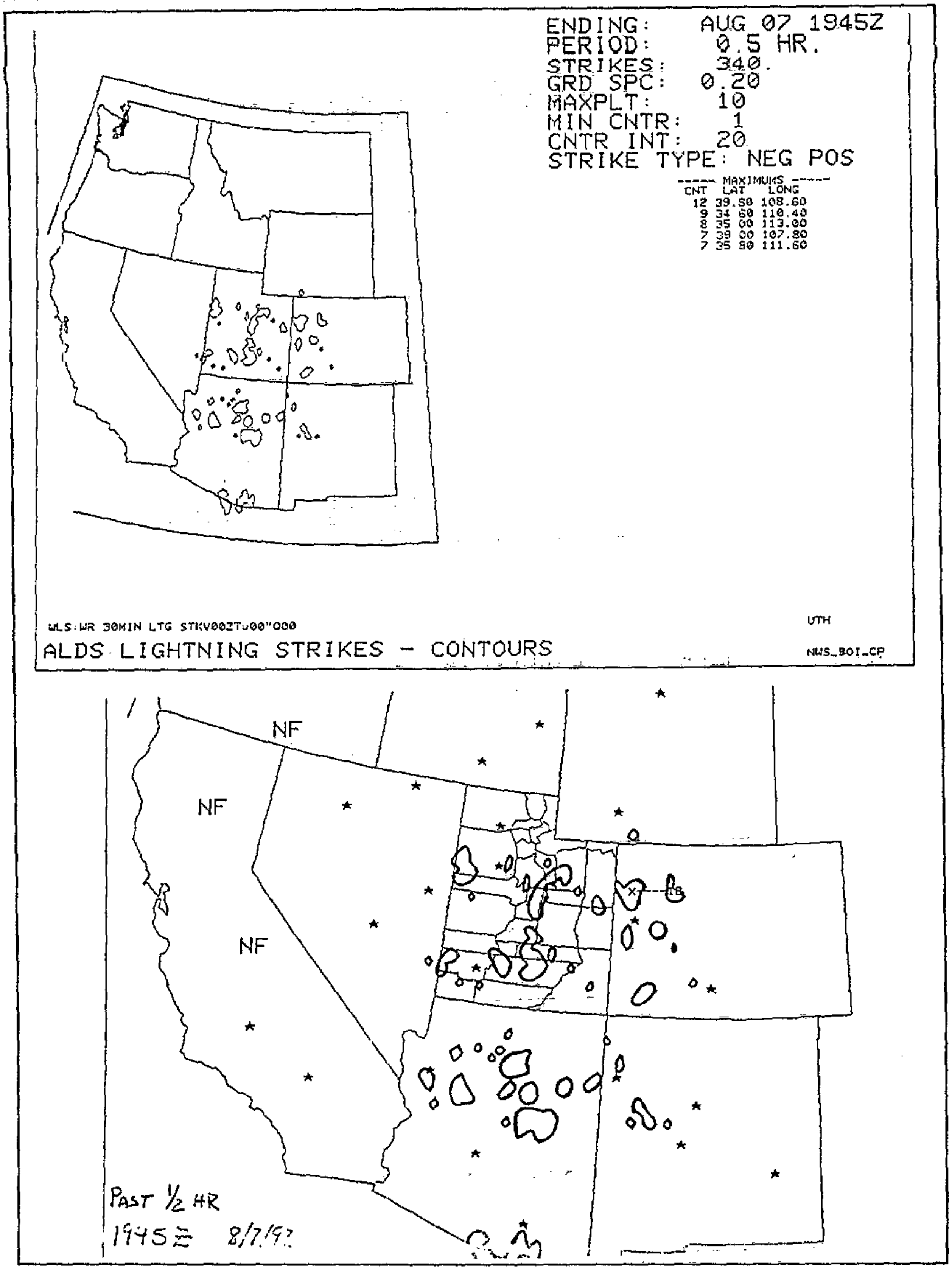


Figure 3. Examples of NWS graphic display of data (BLM Network). Top: Entire network area. Bottom: Zoomed display.

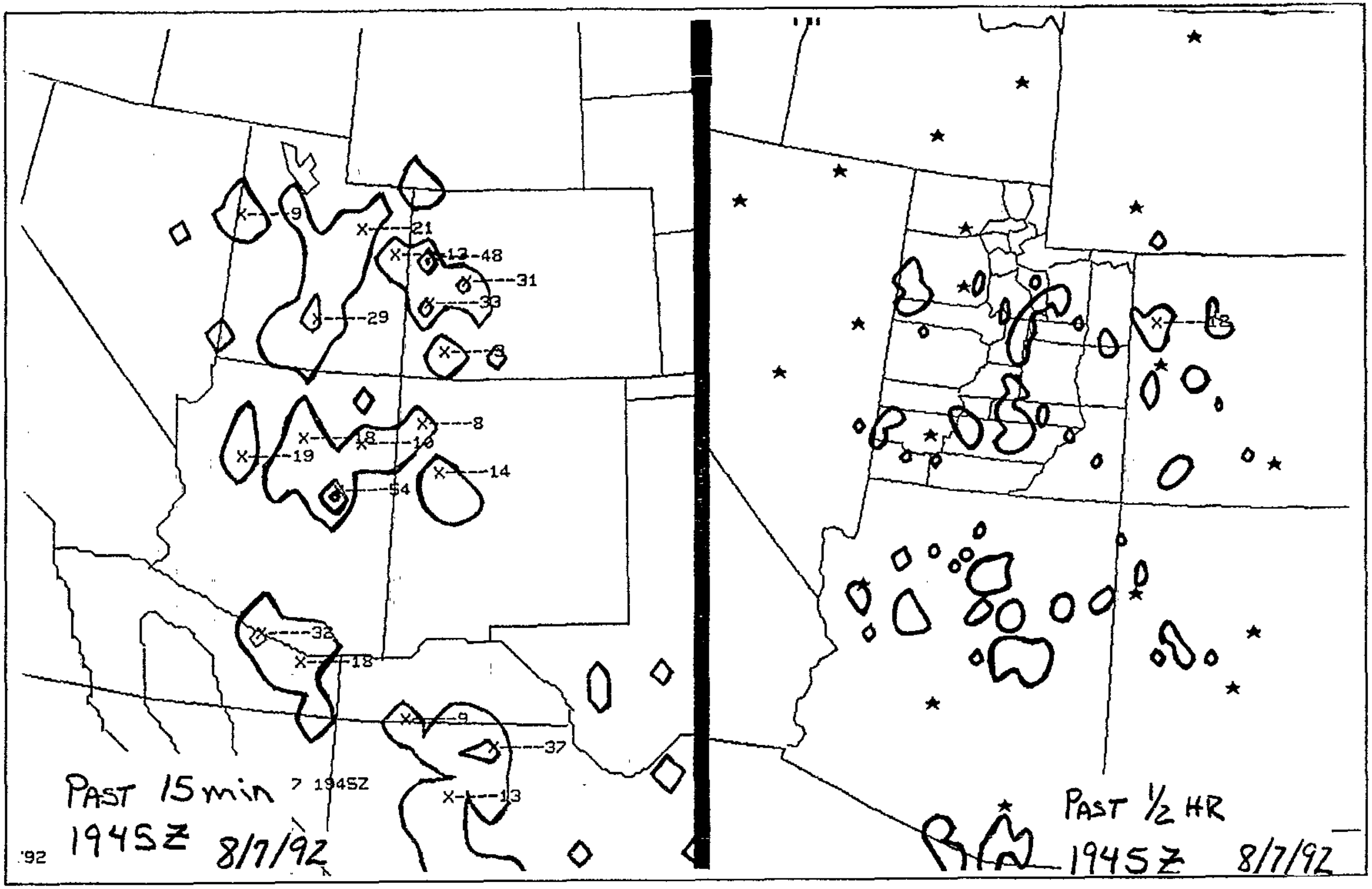


Figure 4. Comparison of NWS zoomed graphic displays. Left: ARSI Network. Right: BLM Network.

LIST OF ATTENDEES
3D LIGHTNING WARNING WORKSHOP

NAME	ORGANIZATION	TELEPHONE	STATUS
Mr. Mike Alexander	ASD/TECOM	(505) 678-1066	S
Ms. Cathy Alirovi	UTTR/2849ABS/DOW	(801) 777-9460	G
Dr. Al Astling	DPG	(801) 831-5101	S
Mr. Terry Battalino	NAWCWPNS Point Mugu	(805) 989-8115	G
Mr. Dan Baumlardt	NOAA/NWS	(801) 549-5131	G
Mr. Sam Bellarosa		(801) 776-9186	G
Mr. Chris Biltoft	DPG	(801) 831-5101	M
Mr. Gerald Boyd		(505) 845-3181	G
Mr. David Casey	NOAA/NWS	(801) 524-4000	G
Mr. Tom Clemmons	DPG	(801) 831-4674	G
Mr. Lloyd Corbett	NAWCWPNS China Lake	(619) 939-6058	M
Ms Laurie Dalton		(801) 776-6500	G
CAPT Eugene Dobry, USAF	DET 4, AWS	(904) 884-5702	S
Dr. Jack Ernst	NASA/WSO	(202) 453-2571	S
Mr. Charles Fain	45 SPW/MADC	(407) 494-2180	M
Mr. Mark Fair	NOAA/NWS/DOE	(702) 295-1232	S
MR. Ed Forness		(702) 295-1141	G
Mr. Nick Gillard	TRW INC	(801) 773-2576	G
Mr. Carl Gorski	NOAA/NWS	(209) 334-9862	G
Ms Brenda Graham	NOAA/NWS	(801) 524-6946	S
MAJ Nancy Harris, USAF	45 SPW/WES	(407) 253-1490	S
Mr. Philip Harvey	AFFTC/510 OSS/WE	(805) 277-4093	M
Mr. Richard Hasbrouck	LLNL	(510) 422-1256	S
Mr. Hal Herring	45 SPW/CSR	(407) 853-8211	M
Mr. John Hoel		(801) 581-7081	G
Mr. Ed Kepple	3246 TW/DOW	(904) 882-5960	M
LCDR Richard Kren, USN	NAWCAC Patuxent River	(301) 863-3174	S
AGC Randall Landis, USN	NOCD China Lake	(619) 939-5081	M
Dr. Don Lathm	FS		S
CAPT Kurt Lutz, USAF	UTTR/2849ABG/DOW	(801) 777-9410	M
Dr. Don MacGorman	NOAA/NWS	(405) 366-0405	S
Mr. Norman Neiman	45 SPW/NYMA	(407) 799-2489	G
LCDR Cynthia Nelson, USN	OFCM	(301) 443-8704	S
Mr. Robert Olsen	WSMR/ASL	(505) 678-1939	M
CAPT Timothy Oram, USAF	WTC	(702) 652-4585	M
Mr. Dave Pike	NOAA/NWS	(801) 524-5523	G
Mr. James Rafferty	DPG	(801) 831-5101	S
Mr. Mike Roberts		(801) 776-0446	G
CAPT John Rogers, USAF	AFOTEC/WE	(505) 846-9424	AM
CAPT Peter Roohr	HQ AWS/XTR	(618) 256-4721	S
LT Stephen Rose, USAF	DET 2, SMC/WE	(408) 752-3902	M
Mr. Robert Shanks	TRW INC	(801) 774-7869	G
Mr. Craig Smidt	NOAA/NWS	(801) 524-5133	G
COL William Smith, USAF	NASA/WSO	(202) 453-2574	AM
Mr. Andrew Stern	NOAA/NWS	(703) 260-0107	S

LIST OF ATTENDEES
3D LIGHTNING WARNING WORKSHOP

NAME	ORGANIZATION	TELEPHONE	STATUS
Mr. Michael Stringfellow	PQE	(801) 977-3429	G
Mr. Donald Thornley	WSMR	(505) 678-3818	S
Mr. Darwin Tolzin	NAWCWPNS Point Mugu	(805) 989-8749	M
Mr. Kiyoji Tomita	USAKA/AEROMET	(805) 238-7994	M
Mr. Dean Weingarten	YPG	(602) 328-6467	M
Mr. Scott Weishaor	NOAA/NWS	(801) 524-5133	G
Mr. John White	DPG	(801) 831-5101	G

Status: M = Member, AM = Associate Member, S = Speaker, G = Guests, V = Vendor

Results

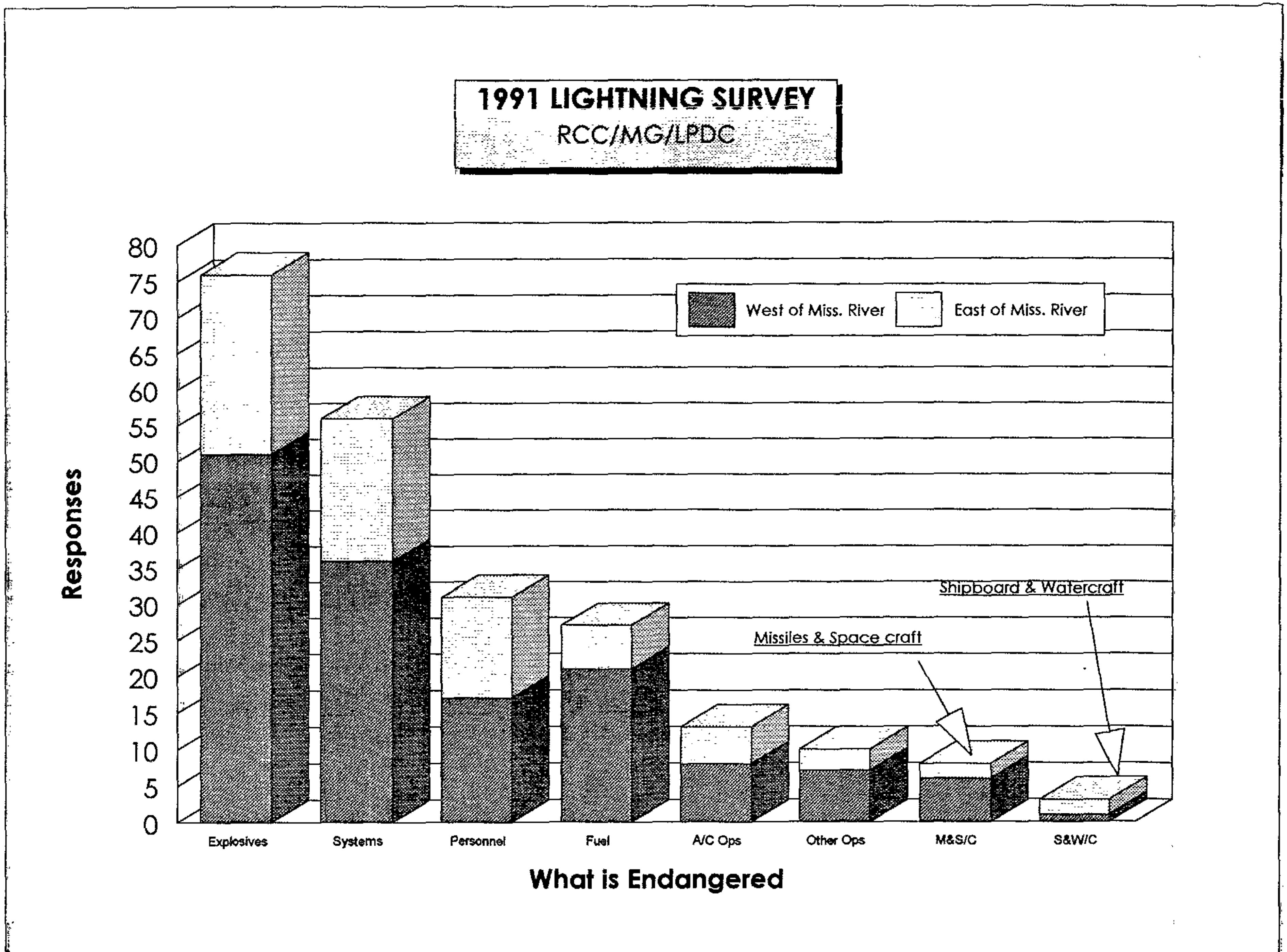
1991 Survey of Ranges

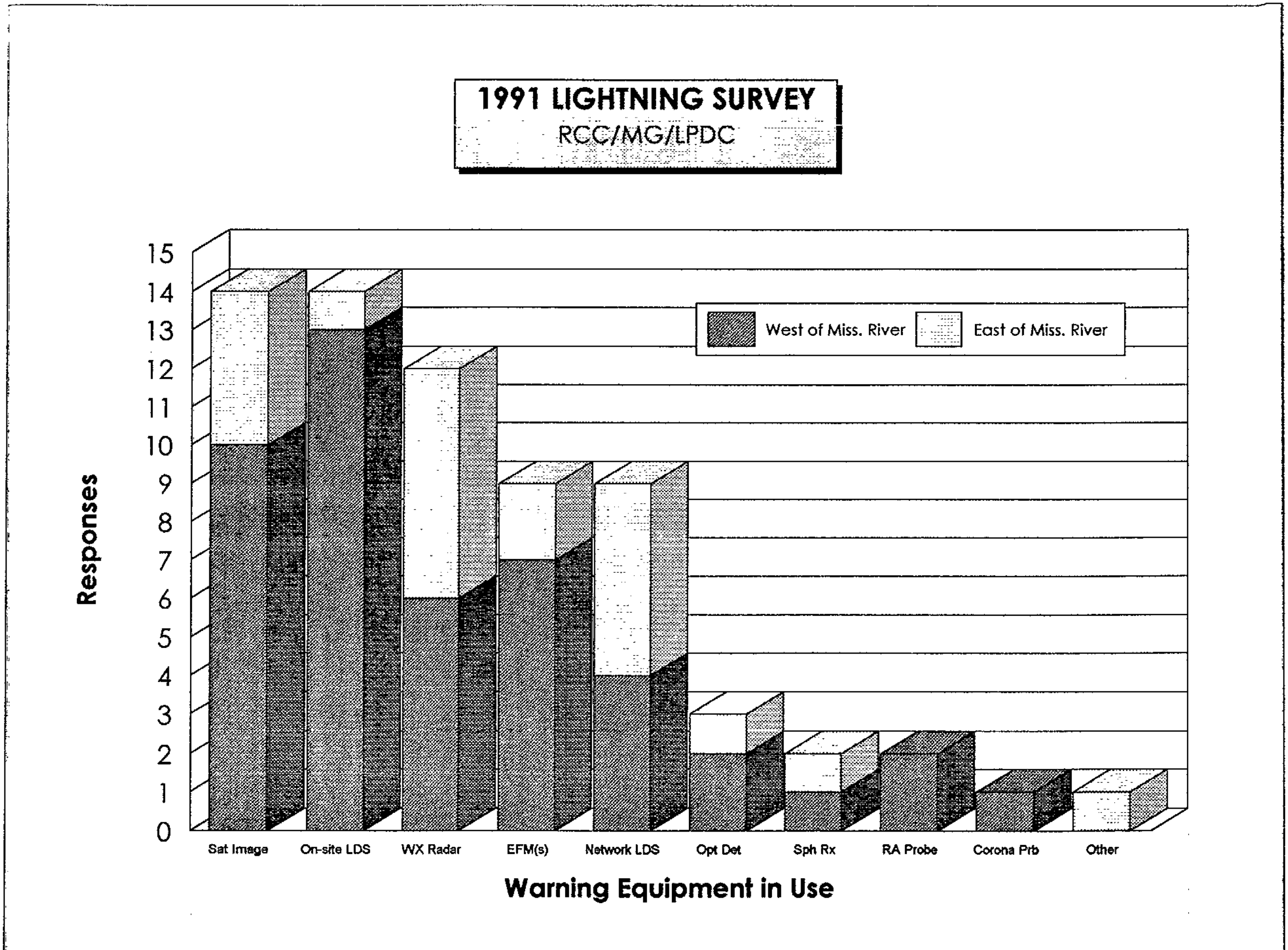
1992 Survey of Workshop Attendees

The 1991 Survey

The LPDC distributed a lightning survey to the test ranges to determine, in part, what was at risk and what lightning warning equipment was being used. Every range responded and a large volume of information was received. The data was divided into two groups, East and West of the Mississippi River, and two (self-explanatory) bar graphs were plotted. Abbreviations used for the *Warning Equipment in Use* graph are as follows:

Sat Image	satellite images
On-site LDS	stand-alone lightning detection system (e.g., magnetic direction finding or time of arrival) located on site
WX Radar	weather radar
EFM(s)	electric field mill(s)
Network LDS	data from large-area lightning detection network (not site dedicated)
Opt Det	optical detector
Sph Rx	spherics receiver
RA Probe	radioactive probe
Corona Prb	corona current probe


1991 LIGHTNING SURVEY
RCC/MG/LPDC
West of Miss. River
East of Miss. River
Responses
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Explosives
Systems
Personnel
Fuel
A/C Ops
Other Ops
M&S/C
S&W/C
Missiles & Space craft
Shipboard & Watercraft
What is Endangered


1991 LIGHTNING SURVEY
RCC/MG/LPDC
Responses
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
West of Miss. River
East of Miss. River
Sat Image
On-site LDS
WX Radar
EFM(s)
Network LDS
Opt Det
Sph Rx
RA Probe
Corona Prb
Other
Warning Equipment in Use

The 1991 Survey (continued)

The following summarizes responses to several survey questions:

What needs improvement?

- verification of detected strikes, and forecasting of first strike within ten miles
- longer lead time
- more precise measurement of electrification thresholds needed to initiate lightning
- cost of lightning-caused losses to show benefits of modern detection systems
- information on *preferred track* phenomenon
- better locational accuracy and sensor coverage
- detection and location system that would augment other thunderstorm prediction tools
- for a *Stormscope* (or equivalent), how much clustering needed to assert presence of lightning?
- better and standardized method of who to call, who issues warnings, and when
- intracloud lightning detection system
- equipment that will warn of static charge buildup under conditions of low relative humidity or strong wind
- information on lightning-precursor phenomena

How can the LPDC help?

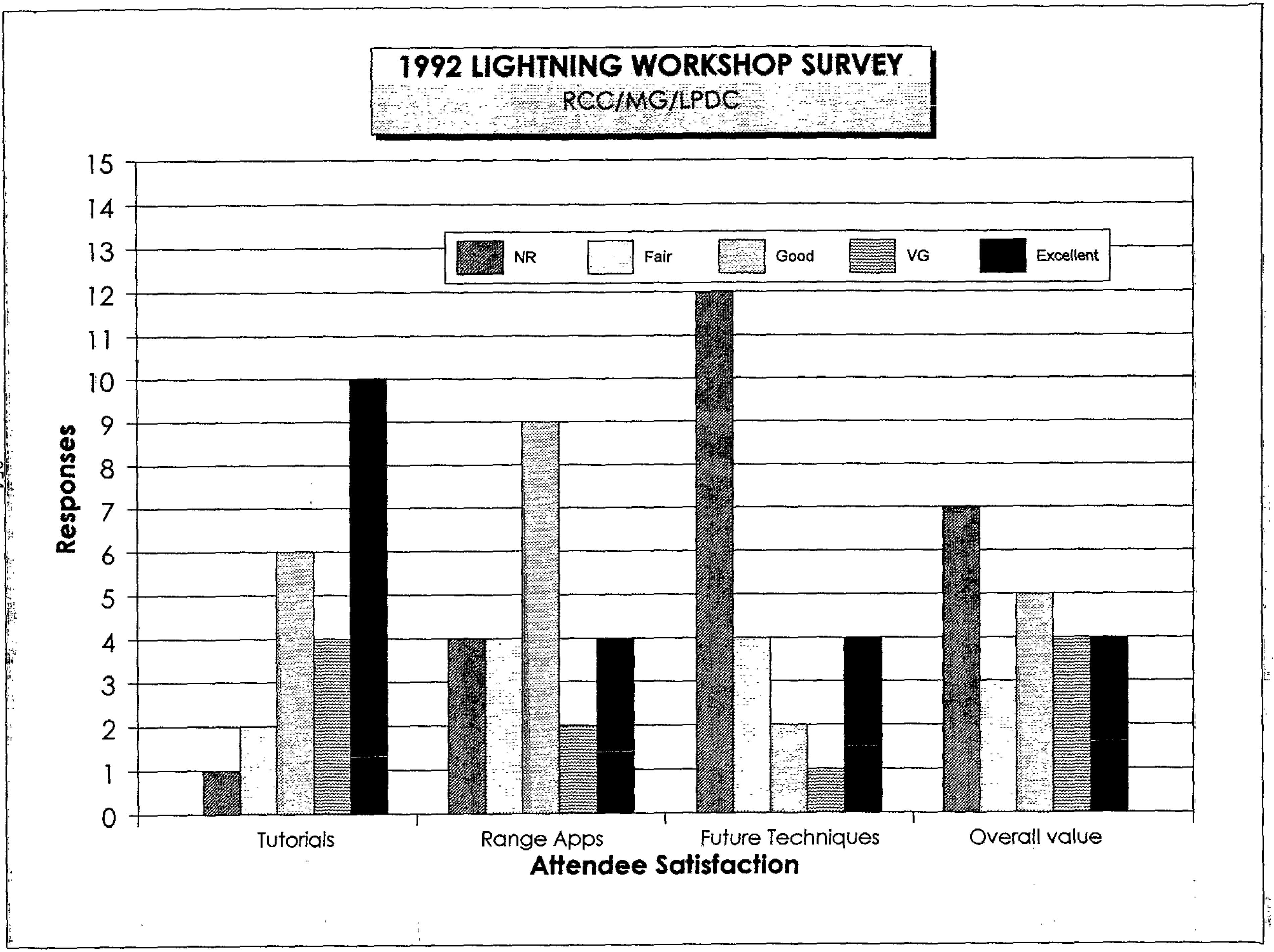
- determine how to improve warning time and cut distance to CG lightning from ten to five miles
- keep abreast of state-of-the-art detection; provide information regarding procedures and equipment in use by various facilities
- identify prediction equipment and programs
- information on the cost effectiveness of reliable warning systems should be made more readily available
- promote sharing of ideas on detection, forecast generation, and dissemination
- facilitate transfer of information regarding detection systems at various ranges
- provide guidance and literature as it applies to Range Operations
- keep ranges informed on technological advances
- provide information on who and where the lightning detection/prediction experts are
- organize conferences/workshops
- promote sharing of forecasting (advisory) procedures using lightning detection

Survey of 1992 Lightning Warning Workshop Attendees

The following table indicates strong interest in future work shops—on a one to two-year cycle—and for having presentations by manufacturers and/or equipment demonstrations in vendors' suites. This needs to be looked at carefully to preclude future workshops from becoming commercialized. The content of any vendor presentation should be strictly technical, and any demonstration should seek to support the that presentation. The *Attendee Satisfaction* bar graph indicates that the tutorials and range applications were very popular. (Note that NR is the number of non-responses for that question.) Although Future Techniques didn't seem too popular, the workshop was generally considered to have been of value.

Should there be future workshops?	Yes	95.6%
	No	4.4%
How frequently should they be held?	Annually	43.5%
	Approximately every 18 months	17.4%
	Approximately every 2 years	40.1%
How much time for tutorials?	1 day	8.7%
	1.5 days	82.6%
	2 days	8.7%
Hold in conjunction with MG meeting?	Yes	69.6%
	No	8.7%
	No response	21.7%
Respondent interested in presenting?	Yes	30.5%
	Maybe	13.0%
	No	39.1%
	No response	17.4%
Should manufacturers make presentations?	Yes	78.3%
	Maybe	8.7%
	No	13.0%
Should manufacturers set up demos in suites?	Yes	73.9%
	Maybe	13.0%
	No	8.7%
	No response	4.4%

(Note: 48.9% of the attendees responded to the survey)



1992 LIGHTNING WORKSHOP SURVEY
RCC/MG/LPDC
NR
Fair
Good
VG
Excellent
Responses
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Tutorials
Range Apps
Future Techniques
Overall value
Attendee Satisfaction

Survey of 1992 Lightning Warning Workshop Attendees (continued)

A summary of comments and suggestions follows:

- case studies—interesting, but should just be overviews
- categories generally appropriate, but presentations were too long
- consider focusing on one main topic
- prepare handouts prior to the workshop
- detector discussions were helpful
- have breakout sessions for special topics of interest to smaller groups
- add INTERNET file for better communications
- name tags were helpful
- future speakers
  - Dr. Fred Moser and Jan Lewis of NSSFC
  - Dr. Steve Goodman, NASA Huntsville
- future tutorials and topics
  - prediction techniques; modeling, statistical methods
  - instrumentation—interpretation of data
  - instrumentation—recommendations for installation and maintenance/calibration
  - lightning warning procedures
  - detection systems and networks
  - analysis of lightning data from LDATS, LLP, etc.
  - electric field mill data and analysis during lightning storm conditions
  - LDAR, doppler radar
  - computer analysis applications and programs (especially for PCs)
  - lightning frequency and storm intensity information (especially for the West)
  - lightning physics, cause and effects of strikes and current transmission
  - physics of protection
  - simulation techniques, hardening techniques, measurements
  - CAPE, CABLE, and SWAMP
  - lightning—basics & refresher; new discoveries; weather cases

Conclusions

The surveys didn't reveal any significant surprises. However, five years have elapsed since the 1st Lightning Warning Workshop, and a lack of uniformity still exists among the test ranges regarding how lightning-warning data is obtained, interpreted, and used. The concerns being expressed today aren't much different from those voiced in 1987. However, by establishing the LPDC and conducting workshops, a network has been created that allows common problems and needs to be identified, and information regarding solutions to be shared. Now, we must communicate these problems and needs to the scientific community and the equipment manufacturers so that solutions can be obtained. And, the RCC/MG should begin to define what standards should be developed to ensure lightning warning uniformity throughout the test ranges.